AIAA-96-2968

Experimental Evaluation of the TIOO-3 Stationary Plasma Thruster and Xenon Propellant System For The RHETT- 1 Program

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ABSTRACT

AT- 100-3 Russian Hall plasma thruster, xenon flow control unit (X FCU) and US xenon propellant subsystem developed for the RHETT- 1 propulsion system arc described. The propellant system includes a pressure regulator, on/off valves, service valve and high/Jew pressure transducers, built to flighl-like standards and assembled onto a mounting plate structure. Testing of the propellant system included experiments to measure output pressure regulation variations through a temperature range of -20 through +30 degrees C with an input pressure rangeof413-6100 kPa (60-885 PSI A). A Russian-designed and fabricated laboratory xenon flow control unit was evaluated over a range of XFCU temperatures, input pressures, and flow rates. The thruster evaluation program included performance testing at various discharge voltage and input power levels, and a 632-hour wear test. Thrust and efficiency of the T-100-3 arc comparable to the SPT- 100. The endurance test was performed for 349 on/off cycles and 632.4 hours of operation at an input power to the thruster of approximately 1.35 kW. Each cycle was nominally 24 hours of thruster on-time and 10 minutes of thruster off-lime. Thrust and thruster efficiency decreased, from 83 mN and 49% at BOL to 81.5 mN and 45% at the completion of the wear test. Thruster mass decreased by approximately 20 g over 630 hours. over the course. of the wear test the peak beam current density in the thruster plume measured on the thruster centerline decreased only slightly. 1'-100-3 plume characteristics are similar to those measured on the SPT-100. Inner insulator wear rates were a factor of three. lower and outer insulator wear rates at certain locat ions were, 30% greater than the. insulator wear rates measured on the SPT- 100. Life estimates for the T-100-3 based on the wear test data arc consistent with life. estimates of the SPT- 100. The flight-like propellant feed system, T-100-3 thruster, and laboratory xenon flow control unit were tested together as a system in vacuum; all subsystems functioned nominally. The thruster, XFCU and XPS then were subsequentl y integrated into the RHETT- 1 propulsion s ystem at Lewis Research Center and tested with a power processing unit and integrated structure.

INTRODUCTION

Stationary plasma thrusters arc gridless ion thrusters that were originally investigated in the US. in the, Carl y 19&Ys [1-3]. However, it was in the former Soviet Union that these thrusters were developed to operate efficientl y and were ultimatel y opti mized to operate at a specific impulse of approximatel y 1,600 s with an efficiency of over 0.5 [4-6]. The SPT was successfully developed during the 1960's and 1970's by Morozov and others to obtain a unique combination of specific impulse and efficiency. Sixty-four SPT-60 and SPT-70 thrusters have flown in space, starting with the Meteor 1 in 1969-1970 [7-9]. The mission success rate for these thrusters is reported to be 100% [9]. More recentl y, 8 SPT-100 thrusters each were flown on the Russian GALS and EXPRESS satellites [9]. Reportedly ail thruster systems arc functioning nominally [1 O].

In 1990 the. former USSR began to make available to the, West data concerning the unique characteristics of these Hall thrusters. In 1991, under a program sponsored by the Ballistic Missile Defense Organization (BMDO) a team of electric propulsion specialists visited the. USSR to experimentally evaluate the performance of a 1.35-kW SPT at the Scientific Research Institute of Thermal Processes in Moscow and at Design Bureau "Fakel" in Kaliningrad, Russia, The evaluation verified that the actual performance of the thruster was close to the claimed performance of 50% efficiency at a specific impulse of 1600 s [111. Studies indicate that for north/south station keeping and Earth orbit raising applications of electric propulsion, the optimum specific impulse is in the range of 1,000-2,000 sec [12]. The combination of the flight heritage of the SPT-70 and the availability of thrusters and thruster data led to substantial interest in these thrusters by Western spacecraft manufacturers for primary and auxiliary propulsion applications. Space S ystems/Loral is presentl y flight-qualifying SPT- 100 thrusters for north/south station keeping and Earth orbit raising applications and plans to provide these thrusters on their

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spacecraft [13]. Recently Design Bureau Fakel, located in Kaliningrad, Russia, successfully completed a 7,000-hr endurance test of an SPT-100 [14].

Since the initial visit to the former Soviet Union in 1991 BMDO has pioneered the introduction of this technology to the west through a variety of programs and activities that include support of Space S ystems/Loral's SPT-1OO qualification program [15-18], evaluation of the thruster with anode layer [19-21], testing of high-power Hall thrusters [22-24], and development of a prototype Hall thruster electric propulsion system called RHETT-1 (Russian Hall Effect Thruster Technology) [25,261. BMDO's objective is to develop ncw electric propulsion technology and support commercialization of that technology through development programs and flight projects.

As part of the BMDO-sponsored test program the T- 100-3 thruster from the Keldysh Research Institute for Thermal Processes (NI 1'1'1') was evaluated. N11'1'1' began work in electric propulsion in 1960 [27]; early efforts centered on multi-mega watt MPD propulsion. By the 1970's thruster development had outpaced power availability in space and NIITP's program was re-directed towards development of laboratory and flight plasma sou rccs for space physics investigations, ground applications for ion sources, and ion sources for controlled thermonuclear fusion. Plasma sources developed at NIITP ftcw as payloads on various missions including Cosmos-728, Cosmos 780, and numerous sounding rocket flights. Ultimately NIITP focused on the development of advanced Hall electric thrusters with a variety of testing and analysis activities that arc described in Ref. 27. Chief among these activities at NIITP are the development of heaterless hollow cathodes [27], an advanced SPT- 100 plasma thruster called the T-100-3 [27], and an advanced propellant flow control system. NIITP has completed wear tests [28] and electromagnetic interference measurements [29] of the T-100-3 thruster, and 20,000 on/off cycles and a 1,500-hr wear test of the.ir heaterless hollow cathode [28].

In 1995 BMDO tasked the Lewis Research Center (LeRC) to develop RHETT-1 (Russian Hall Effect Thruster Technology), an integrated Hall electric thruster propulsion system [26]. The goal of this program was to build a system as ftight-like as possible that would reduce the cos1 and risk of developing flight Hall thruster systems. The T-100-3 from NIITP was selected for this system.

JPL's responsibilities in the RHETT- 1 program were to procure and test the propellant storage and distribution system (PSDS), evaluate a xenon flow control unit (XFCU) designed and fabricated at NI 1'1'1', evaluate and wear test the T-100-3 plasma thruster, test these three subsystems together as an intc.grated system, and provide these subsystems to LeRC to be integrated into the RI HETT- 1 propulsion system. The thruster, XFCU and XPS then were subsequently integrated into RHETT- 1 at Lewis Rc.search Center and tested with a power processing unit and integrated structure [26]. This paper presents the results of an evaluat ion of the. PSDS, the XFCU, and the T-100-3. Results of a 630-hr thruster wear test arc also described.

APPARATUS

A photograph of the 'r-1(03 plasma thruster developed at NIITP and used for the RHETT- 1 evaluation is shown in Fig. 1, The T-100-3 included two heaterless hollow cathodes and had bear operated at NIITP for approximately 20 hours prior to testing at JPL. The outer insulator which forms the outside discharge chamber wall was approximatel y 121.9 mm-d i a, and the outer diameter of the inner insulator was 69.8-mm. The thickness of the outer and inner insulators were 10.8 mm and 9.0 mm respectivel y. In the 630-hr endurance test the cathode at the top (cathode #1) was used as the primary cathode. The unused cathode (cathode #2) was covered with a tantalum shroud to reduce contamination to this cathode during the wear test.

The endurance test was performed in a 3.1-m dia. x 5.1-m stainless steel vacuum chamber equipped with three, each, 1.2-m diameter helium cryopumps. The minimum no-load tank pressure 8.4 x10-6 Pa (8.4 x 10-8 I'err). The measured pumping speed on xenon for the three pumps combined is approximately 48,000 1/s. A probe rake, consisting of 25 Faraday probes of diameter 2.3 cm, mounted on a semicircular arc 2.4 m in diameter was used to examine the thruster exhaust. The facility and plume probes arc dc.scribed in detail in Ref. 30.

The thruster was mounted near Onc end Of the vacuum tank, directly facing a cryopump positioned at the other end of the chamber. A chevron-shaped beam target was placed at the opposite end of the vacuum chamber to reduce backsputtering of beam target material to the thruster and is described more completely in Ref. 30. Due to the beam divergence characteri sties of Hal 1 thrusters, material can also be sputtered from the vacuum tank sidewalls and deposited onto the thruster. Therefore the cylindrical side walls of the vacuum chamber were also lined with graphite panels. Glass slides were placed 21 cm to either side of the thruster such that material back sputtered to the. thruster could be quantified and characterized. A photograph of the T-100-3 mounted inside the, vacuum chamber is shown in Fig. 2.

Tank pressure was measured using two ion gauges. One gauge tube was mounted to the. side wall of vacuum tank; the other tube was mounted inside the vacuum tank, approximatel y 0.51 m above and 0.58 m behind thruster'. This tube was calibrated on both xenon and nitrogen using a spinning rotor gauge that is traceable to the National Institute for Standards and Technology (NIST).

A laboratory propellant system was used for supplying xenon to the T-100-3 for the endurance test and is described in Ref. 30. The xenon supply pressure was

measured using a capacitance manometer that was calibrated to an accuracy of ±0.25% at 249.94 kPa. Micrometer valves located inside the vacuum chamber were used to control the flow rates to the discharge chamber and cathode. The pressure in the propellant tubing was above atmospheric pressure up to the. micrometer valves. This design may prevent cathode poisoning because those parts of the propellant system that arc below atmospheric pressure are located inside the vacuum chamber. The purity of the xenon used by the. T-100-3 was tested directly from the xenon bottle. Sample data indicate that the purity specifications (99.999%) were exceeded. Finally a xenon purifier supplied by N] ITP was placed immediately upstream of thruster inside the vacuum system.

Thermal mass flow meters were used to measure the discharge, and total propellant flow rates. The cathode flow rate. was calculated by subtracting the discharge flow from the total flow rate. The flow meters were calibrated using a bubble volumeter which was tested at NIST. Test data indicated that at the nominal xenon flow rate of the 3'-100-3 (approximately 55 seem) the flow rate measured with the JPL bubble volumeter was approximately 1% lower than the flow rate measured with N] ST equipment [31]. The, difference is attributed to diffusion of xenon through a rubber hose used in the J Pl, bubble volumeter. The bubble volumeter data on xenon were curve fit and the curve fit was incorporated into the SPT data acquisition and control program. Flow rate calibrations were performed approximately every 100 hours.

The T-100-3 was mounted to an inverted pendulum style thrust stand of the type developed at NASA LeRC [32]. In this design, thrust is indicated by a linear voltage displacement transducer (1 .VDT). The thrust stand was surrounded by a water-cxrdcd housing to minimize thermal effects on the measured thrust; the thrust stand housing can be seen just below the, 1'-100-3 in Fig. 2. The thruster was mounted to the thrust stand but was electrically isolated from the thrust stand arrd facility ground. The T-100-3 was radiation-cooled through usc of an aluminum plate that was flocked with carbon fibers to increase it's cmissivity [33]. Thermocouples were attached to the thruster bod y and to the radiator plate center and radiator plate corner. The thrust stand inclination was adjusted continuously under computer control to improve the accuracy of the thrust measurement over extended test times. IWrd-weight thrust stand calibrations were performed in-situ throughout the wear test. Repeatability of thrust stand calibrations was ≤1.5%.

Thrust is dctcrmincd from the difference in the LVDT voltage with the thruster on and off, The most accurate way to determine the "thruster oft" LVDT voltage is to measure. the LVDT voltage within onc second of the thruster being turned off; in this way thrust stand drift duc to thermal or other effects arc minimized. However, thrust measured using this procedure dots not include the small thrust element duc to expansion of hot xenon out of the thruster. Total thrust measurements for the. T-100-3 reported herein arc the sum of the electrostatic thrust plus an estimate of the thrust provided by the hot xenon flowing through the thruster. The estimate for thrust duc to expansion of hot xenon out of the thruster was calculated using the following formula:

$F = Md(8kT /]Im)^{1/2}$, where

F = Thrust duc to expansion of xenon out of tbc D-100 (Nt)
Md = Discharge flow rate (Kg/s)
k = Boltzman's constant
T = T-1OO body temperature (K)
n] = Xenon mass (2.18×10^{-25} Kg)

The thruster was operated using laboratory power supplies for the. discharge and cathode ignitor. The discharge voltage was fixed at approximately 300 V. An output filter designed and fabricated by Space Power, Inc. was placed across the thruster anode/cathode to reduce the amplitude of discharge current and voltage oscillations. The thruster was turned on when the cathode was ignited. Thruster starting was performed manually. The discharge current was used to supply the excitation current required for the thruster electromagnet coils.

A DC high voltage start supply across the ignitor and cathode emitter was used to start the. cathode. The heaterless NIITP hollow cathode is started at room temperature without any preconditioning of the cathode emitter. N11"1'P has demonstrated over 20,000 err/off cycle.s and 1,500 hours of steady-state testing of their heaterless cathode [28]. NIITP now offers a version of their hollow cathode that includes a cathode conditioning beater [34]. The cathode was started at a flow rate of approximately 2 mg/s, and after thruster ignition the cathode flow rate was reduced to the nominal operating value of 0.37 mg/s.

Steady-state thruster operat ion and shutdown sequencing were controlled by a PC bawd data acquisition (DAC) system. This system also monitored the vacuum facility enabling unattended operation. A total of 56 channels that included thrust, xenon mass flow rate, anode voltage. and current, floating voltage, magnet current, tank pressure and various other facility components Were monitored and recorded as a function of time. The data were averaged in real ti mc and the averaged value.s were displayed on a monitor and recorded on the computer hard disk drive. every 3-60 seconds; higher data recording rates were used during the first 30 minutes and last 5 minutes of thruster operation to examine various thruster operating characteristics and to obtain more precise thrust measurements.

If certain engine or facility parameters exceeded specificat ions, the computer opened a relay between the thruster anode and the discharge power supply to terminate thruster operation, and activated a telephone dialing machine (autodialer). Xenon flow through the cathode and discharge remained on; there was no active computer

control of the. flow rates to the anode and cathode. The computer sent a change-of-state signal every 15 seconds to an electronic timer (heartbeat box); in the event of a computer failure, the timer activated a series of relays to remove PCU power and activated the autodialer. The data storage interval during thruster operation was typically every thirty seconds. The data storage rate during thruster start-up and shutdown was increased to every three seconds 10 improve thrust measurement accuracy and to record Iran sient thruster data.

Discharge current and electromagnet current were measured using calibrated current shunts. The. discharge current calibration was determined using a voltmeter which averages the, direct-current value of the discharge current shunt voltage drop over a period of four seconds. Oscillations in the discharge current were measured with an inductive probe placed on the discharge current cable close to the vacuum tank feed through. The discharge voltage ripple was measured at the vacuum tank feed throughs as well, using a combination inductive/Hall effect probe. Cabling length between the vacuum chamber feed through and T100-3 was approximatel y 6 m,

The thruster was photographed (from an off-axis view) periodically through a window in the vacuum system to document the condition of the thruster. Insulator thicknesses were determined from photographs by measuring the ratio of insulator width to the outer diameter of the outer insulator or inner diameter of the inner insulator. The T-100-3 can be seen operating in the endurance test facility in Fig. 3.

PROCEDURE

The T-100-3 discharge and cathode #/1 were purged with xenon when the mechanical pumps were used to pump the vacuum tank from atmosphere to 50 mTorr. The T-1003 was operated only if the vacuum tank base pressure was below 2.7 x 10-5 Pa (2 x 10-7 Torr). During a facility shutdown (cryopumps off) the 1'-100-3 was purged with xenon, The thruster was turned on by energizing the discharge supply and igniting the cathode. Cathode igniter voltage was set at 250 V; if the cathode did not start at this voltage the ignitor supply voltage was increased until cathode ignition occurred.

An operating cycle was defined as any time the thruster achieved a discharge current of >1.5 A. The first 35 cycles of the wear test were used to evaluate the performance of two different T-100-3 thrusters, test the data acquisition and control program, the vacuum facility, and the probe rake. In these cycles the thruster were operated for varying time periods, from less than one, minute to over 60 minutes, and at varying discharge currents and discharge voltages.

Discharge voltage was measured between the anode and cathode emit ter, at the vacuum tank feed through. Discharge current and magnet current were measured across calibrated current sh unts and through current meters. Magnet voltage was measured across the magnetic coils at the feed-through. Floating voltage, measured between the cathode emitter and facility ground, and thruster hod y voltage (defined as the potent ial between the thruster body and facility ground) were measured at the vacuum tank feedthrough. The computer data for thruster currents and voltages were calibrated and compared to data taken at the vacuum tank fed-through with hand-held volt meters throughout the wear test.

During wear test cycles the computer performed the task of removing power to the thruster, taking/storing thruster and system data, and monitoring the facility. At the beginning of every cycle the ftow meter voltage wi th no flow was measured. Oscilloscope traces of the discharge current and discharge voltage. were obtained roughly two times every cycle. Approximately every 100 hours the life test was interrupted for a short period of time 10 photograph the thruster, perform flow rate calibrations and to rc-calibrate the thrust stand. 11 thrust stand calibrations and 6 flow rate calibrations were performed during and at the compaction of the wear test.

Thruster start-up procedure was as follows: thruster discharge flow was set to 4.7 mg/sec and the cathode flow to 2 mg/sec. Discharge voltage was set to 300 V on the discharge power supply, and cathode ignitor voltage was preset to 250 V, Computer storage frequency was set to every three seconds. The igniter supply was turned on, which normally resulted in cathode ignition and thruster start. If the cathode did not start the cathode ignitor voltage was increased until cathode ignition was acheived. After thruster start the cathode flow rate was re-adjusted to it's nominal value of 0.37 mg/sec.

RESULTS. ANL) DISCUSSION

1. Preliminary Evaluation Of T-1OO-3

Two different T-100-3 thrusters, dc.signaled #10 and # 11, were characterized. Both of the T- 100-3 thrusters were tested at NIITP for approximately 20 hours prior to being shipped to JPL. A summary of the performance characteristics of these two thrusters is shown in Table 1. Efficiency calculations include cathode. mass flow rate and magnetic coil power.

II. WEAR TEST I) ATA

A. Wear Test Significant Events

A summary of significant events that occurred during the wear test is shown in Table 2. Cycle number vs. operating hours for thruster #11 arc plotted in Fig. 4. The T-100-3 (#11) completed 49 starts and 632 hours of operation over the duration of the wear test. ~'here were no shutdowns required duc to abnormal thruster operation.

A total of 35 cycles were operated at various time intervals to test the thruster or DAC system. During the

wear test four shutdowns were commanded by the computer due to power grid surges, or to some aspect of thruster operation, such as floating voltage, that exceeded it's operational limit.

A laboratory power supply was used 10 start the cathode. The NIITP hollow cathodes provided with the thruster do not have a tip heater for prc-heating and cathode conditioning, rather the cathodes are started at room temperature. Initially cathode #1 could be started using the laboratory power supply at 250 VDC, however by cycle41 the cathode could not be started reliably even at 500 WC, and greater voltages (up to 1000 VDC) were required for start. It should be pointed out that a cathode ignitor built by SPI, Inc. that provides pulsed high voltage (in excess of 1,000 V) to the ignitor never failed to start the cathode. The SPI igniter supply was not available. to JPL during the T- 100-3 evaluation program.

The variation in discharge current as a function of time for cycle 56 is shown in Fig. 5. in wear test cycles prior to cycle. 37 discharge current was approximately constant during the first 30 minutes after start. However, by the beginning of cycle 37 it was observed that discharge current increased substantially, up to 6 A, then decreased, even though the main flow rate was unchanged. This effect increased to a maximum during cycle 50, then the magnitude of increase in the discharge current began to decrease. By the end of the wear test the. discharge current only increased by 1.4 A before reducing again 104.5 A.

Also shown in Fig. 5 arc thermocouple data for the thruster body, plate center and plate corner, with the, thruster radiating to the facility walls that were at a temperature of approx imately 23 degrees C. In the wear test the thruster was connected to a large radiator plate; both the plate and thruster were electric.ally and thermally isolated from the thrust stand with ceramic stand-offs. The data indicate that at a discharge of 300 V and 4.5 A the thruster reaches a steady-state temperature of 230 degrees C approximately 2.75 hours after the thruster is started. Temperature profiles after thruster shutdown are shown in Fig. 6. The data indicate that if the thruster radiates to approximately 300 K the thru ster temperature approaches facility temperature in approximate.] y 2.75 hours.

B. lest Data For Cycles 36-69

Computer data for T-100-3 efficiency, discharge current and voltage, thrust and specific impulse for cycles 26-69 arc shown in Figs. 7-12. The data were measured near the cud of each wear test cycle. Thruster data were analyzed to determine cycle-to-cycle changes in thruster operating characteristics. Thrust was determined by subtracting the LVDT voltage immediately after the l'-100-3 was turned off from the LVDT voltage obtained from averaging the LVDT voltage over the last iwo minutes of the cycle, and mul tipl ying by the appropriate thrust stand calibration factor. To this thrust measurement was added a thrust val ue calculated as discussed in the Apparatus section of this paper. Efficiency and specific impulse were calculated using the values for thrust, total mass flow rate, and engine power (including magnet power), averaged over the last two minutes of the cycle. The discharge flow rate data were not corrected for backflow.

Discharge current, discharge flow rate, and cathode flow rate arc plotted as a function of thruster operating hours in Figs. 7-8. The data indicate that the flow rate required for a discharge current of approximately 4.5 A increased over the course of the wear test, from 4.77 mg/s to 4.97 mg/s; the change in discharge flow rate for a fixed discharge current occurred in the first 200 hours of thruster operation.

The T-10(-3 cathode emitter was floated with respect to the vacuum facil ity and was isolat cd from the. thruster body. The thruster body was electrically isolated from the thrust stand and the cathode emitter. Floating potential and thruster body voltage arc plotted as a function of thruster operating hours in Fig. 9. Floating voltage increased with operating hours to a value of approximatel y -14.0 V until approximately 339 hours into tile wear test, then decreased to -13.3 V wiih 534 hours of thruster operation. The floating voltage then began to increase, but decreased after 600 hours, then again increased.

Floating voltage and thruster efficiency arc plotted as a function of thruster operating hours in Fig. 10. The thruster efficiency slowly decreased until 439.4 hours, where the efficiency decreased sign ificantl y. Thruster efficiency then increased along with floating potential until 600 hours, where the floating potential decreased but thruster efficiency remained essentially unchanged.

Thrust and floating potential arc plotted as a function of thruster operating hours in Fig. 11. There is a correlation between thrust and floating potential similar to that noted for efficiency and floating potential. The data indicate that tile thrust remained approximatel y constant until 439.4 hours, where the thrust decreased significantly over a period of approximately 100 hours. The thrust decrease tracks with decreasing floating potential until after 600 hours of thruster operation, whereupon the thrust increased, possibly because of increased discharge current. With 650 hours of thruster operation the thrust and efficiency of the T-1 W-3 arc similar to values obtained from the SPT- 100 [30] and the N] ITP 't"- 100 wear test [28]. After approximately 600 hours of wear testing at NIITP thrust was measured to be approximatel y 8 1.S mN [28].

Thrust and efficiency arc plotted as a function of thruster operating hours in Fig. Efficiency tracks very well with the floating voltage. No explanation can be given at present to describe the changes in thruster efficiency that were observed in the wear test.

Stcaciy-state. thruster body, plate center and plate comer thermocouple data for all cycles is plotted in Fig.

13. The large decrease in thruster body temperature at 76.7 hours of thruster operation was due to a short operating time (0.35 hours) because of insufficient discharge flow rate. The thruster body temperature was approximately 230 degrees C for the duration of the test, with a slight decrease to approximatel y 227 degrees C near the end of the test. The radiator plate temperatures were approximatel y 125 degrees C at the complet ion of the wear test.

C. Plume Characteristics

The current density measured by the center probe of the probe rake for two different cycles, cycle 36 and cycle 69, arc compared in Fig. 14 and Fig. 15. The distance between the probe and the downstream face of the 1'-100-3 was approximately 114 cm, similar to the distance between the probe and the SPT-100 [30]. The probe was covered with plasma-spray-coated tungsten to reduce the secondary electron emission coefficient [30].

~'here appears to be little change in the shape of the exhaust plume over 624,4 hours, except that the peak current density at cycle 69 decreased, relative to the current density near the start of the wear test. A magnified view of the peak current densities for cycle 36 and cycle 69 arc shown in Fig. 15. The plume divergence angle, defined as the plume full width at half maximum, is approximately 16 degrees. The plume data for the 1'-100-3 are very similar to plume data from cycle 863 (hour 640) of the SPT-100 wear test [30, 34]. The full width at half maximum for the SPT- 100 with 640 hours of thruster operation was approximatel y 16 degrees.

1). Post-Wear Test Inspection

After the completion of the wear test (cycle 69) the vacuum chamber was opened and the. thruster was examined and photographed. The wear data described in sections D. 1 and D.2 below were obtained from the physical inspection performed after the vacuum chamber had been opened.

D.1. insulator Erosion

Erosion of the discharge chamber insulator surfaces was documented photographicall y. Erosion data arc depicted schematically in Fig. 16. The data indicate that the inner insulator wear rate. was about a factor of three lower compared to the WI'- 100 [18], and the outer insulator wear rate was similar to the SP'i'-100 except diagonally across the electromagnets, where the T-100-3 wear rate was approximately 30% greater than the wear rate for the SPT- 100. NIITP observed similar insulator wear rates in their 2,000-hr wear test [28]. However, since the T-100-3 outer insulator is thicker than the SPT-100 insulator, 1'-100-3 operating life due to insulator erosion should be comparable to the SPT-100 if life time estimates arc based on insulator wear rates.

1).2, Cathode Erosion

Cathode erosion is represented in the schematic diagrams in Fig. 17. The outer portion of the unused cathode igniter did not appear to erode substantially. In 632 hours of operation the inner diameter of the unused ignitor cover increased by 1 mm, from 12. mm to 13 mm,

The used cathode ignitor cover OD decreased, from 21 mm to 19.7 mm. Molybdenum eroded from the igniter was found deposited on areas of the thruster body that faced the used cathode. The inner diameter of the used igniter increased by 1 mm, from 12 mm to 13 mm, The thickness of the igniter cover decreased, from 4.8 mm ncw to 4.3 mm at the crrd of the wear test. It is likely that the first failure mechanism for the T-1OO-3 will be cathode ignitor erosion, in which the. igniter erodes too much for proper cathode ignition, deposits from the igniter contaminate the cathode emitter, or a short circuit develops between the. ignitor and the cathode emitter.

D.2. Thruster Mass Loss

Thruster mass at the beginning of the wear test was 3.525 Kg, anri after 632 hours of testing the 1'-10(-3 #11 thruster weighed 3,505 Kg. Total mass loss during the wear test was approximately 20 g.

II. Post-Wear Test Thruster Evaluation

After the thruster was examined and photographed the vacuum chamber was closed and pumped down and additional thruster performance characterization was performed. Fol lowing this, the vacuum chamber was opened, and the thruster was packaged and hand-carried to NASA I.eRC to compare performance measured there with the performance measured at JPL. The daia for the last wear test cycle. (eye.lc. 69), performance characterizations at JPL made after completion of the. wear test and after the vac rrum chamber had been opened, and performance measured at I.eRC arc shown in Fig. 18. The data indicate that thruster efficiency and specific impulse, measured at J }'1. after the vacuum chamber was opened following the WC-M test, was essentially unchanged. Efficiency and lsp measured at JP1, after completion of the wera test 0.453 and 1560 s respectively. Measurements al I.eRC for efficiency and specific impulse were slightly higher than the measured efficiency and Isp at JPL; efficiency was approximate.ly 0.465 and specific impulse was 1575 s. However, performance measurements at JPL and I.eRC are very similar considering the uncertainty in the thrust and mass flow, and differences in laboratory test set- up.

111. Xenon Flow Control Unit (XFCU) Tests

A. Description of the XFCU

The purpose of the xenon flow control unit (XFCU) is to maintain the proper xenon flow rate to the 't'- 100 thruster. In order to maintain a certain discharge current at a given applied voltage, the anode flow rate has

to be maintained at a certain value. This is accomplished by using a thermo-throttle. Adding heat to the xenon flow by resistively healing part of the xenon tubing changes the viscosity of the xenon, The viscosity of xenon increases with increasing temperature of the gas, which is contrary to the behavior of many liquids. Higher heat loads produced by higher thermo-throttle currents increase the viscosity and consequently, for a given feed pressure. (in the following also referred 10 as plenum pressure), decrease the flow rate. Conversely, reducing the throttle current and thus the heat load to the xenon increases the flow rate.

The flow control unit used for the RHETT-1 program was built by NIITP. The unit features redundant flow paths to control each of the anode (or main discharge), cathode and cathode start-up flows, At the design inlet pressure to the XFCU of 2.02 x 10' Pa (2 atm) the respective flow rates were to be maintained at 4.5 mg/s of xenon to the main discharge, 0.3 - 0.4 mg/s to the cathode and 1.6 mg/s through the cathode start-up line. The higher flow to the cathode is required to start the heaterless hollow-cathode.

Flow control is achieved through a series of solenoid valves, passive flow restrictors and active thermo throttles. All flow control devices, including the redundant flow paths, arc placed into an approximately 64 mm wide, 54 mm tall and 195 mm long housing. The entire assembly (excluding electrical connectors) weighs 5S7.8 gram. Adding the weight of the electrical connectors increases the weight to 586.8 gram. The unit features a single propellant inlet. The tubing (inlet and outlet) is specified at 2 mm OD and was measured at 1,98-1,99 mm OD. The tubing wall thickness is roughly 0.5 mm. A 3 mm OD end stub features metric Russian fillings similar to the S wagelok® fittings known in the WCSL The...c fittings feature an internal M8x1 thread. The tubing is made from a Russian steel containing 12% Cr, 18% Ni and 9 %Ti..

The flow schematic of the XFCU is shown in Fig. 19. The inlet tubing leads to a pair of solenoid isolation valves via a tee-joint that splits the flow path into the two redundant branches. In the following, these branches will bc referred 10 as A1/K 1 and A2/K2, using the NIITP notation. The solenoid valves could not bc weighed individually since they were receiverd at J]']. assembled into the XFCU. However, NIITP data indicate a weight of 35 gram pcr valve. The valves require a voltage of 27 Vdc to open, however, as will bc shown below, tests revealed that the valves arc able to open at significantl y lower voltages, down to 15 Vdc.

Following the isolation valves, within each branch, A1/K 1 and A2/K2, the flow path splits up further into anode (main discharge), cathode and cathode-start-up paths. Each path features a solenoid valve identical to the type used for the isolation valves. Following the valves is an active thermo-throttle in the case of the anode, flow path, and passive flow restrictors in case of the cathode and cathode start-up paths. Within the thermo-throttle itself the flow path is split up further into three parallel tubing segments about 2-3 cm in length. Diameters of these tubing segments were not measured, however, the ODs arc significantly smaller lhan tbc 2mm inlet tubing. Current passed through the walls of these three tubing segment heals the xenon flow. By splitting up the flow into those three parallel, narrower flow passages, better heat transfer to the xenon flow and a flow restriction effect is achicvcd. The flow restrictors in the cathode and cathode start-up branches consist of appropriate lengths of small diameter tubing (not measured) wound into coils to accomplish the necessary flow reduction. The anode path then connects to an outlet tubing of the, same dimensions as the inlet tubing. Cathode and cathode. start-up flows are first joined via a tee-connection and then also connect to the same size outlet tubing as the inlet. Given the two redundant branches A 1 /K 1 and A2/K2, the flow control unit thus features four outlets (2 anode and 2 cathode outlets) and onc central inlet.

A four pin Russian-built electrical connector provides the electrical interface to the two thermo-throttles of the. unit and a ten-pin connector provides the interfaces for the eight solenoid valves. Eight negative. lines and two positive lines connected to all eight valves with onc serving for redundancy make up the ten-pin connector. Throttle resistances were measured at the connector as 0.20 Ω for the throttle of branch Al/K 1 and 0.21 Ω for the A2/K2 throttle.

B. Test Set-up and Procedure

The XFCU was installed in the 3m dia., cryopumped vacuum chamber already described earlier. The unit was placed near the thrust stand, roughly 35 cm away. The XFCU was connected to a propellant feed system located in a control room adjacent to the vacuum chamber, separated from the tank by roughly 8 m of 1/4 inch (6.35 mm) tubing. The feed system, shown in Fig. 20, was originally dc.signed for ion engine operation and thus features main, cathode and neutralizer ports. The XFCU inlet was connected 10 the pump out line, originally used to pump out the feed system via the vacuum tank and its pumping facilities. The flow system was modified from its usc in the XFCU tests by installing an additional flow meter into the line. connecting the feed system to the xenon supply. The redundant anode and cathode X FCU outlets, respectivel y, were joined prior 10 being connected to the anode inlet and onc of the two thruster cathodes of the T- 100. During another set of tests, aimed at determining leak rates through XFCU valves, the anode and cathode outlets of the unit were again joined, but subsequently connected to the main and cathode ports of the. feed system shown in Fig. 20, respectively. Pressure gages mounted to the main and cathode calibration ports shown in Fig. 20 were able to measure pressure raise and allow determination of valve internal leak rates.

Some of the tests performed with the XFCU required operation of the unit at lower than room

temperatures. For these tests, the XFCU was placed on a copper cold plate. A Glycol bath located outside the vacuum chamber was cooled by two cold lingers connected to onc cooler each. A pump circulated the glycol via a vacuum feed through to the copper cold plain, The XFCU was further shielded by MLI blankets wrapped around the unit to protect it from heat radiation from the surrounding vacuum tank, which was at ambient temperature. Temperature sensors located on the XFCU and the cold plate recorded the temperature values. This set-up allowed temperatures as low as 2.6 C at the XFCU at beginning of operation, before the unit started warming drrc heat dissipated in the opened valves and the thermo throttles. The corresponding temperature of the cold plate at this point of operation was -1.2 C.

Two DC power supplies provided the necessary power for valve actuation and the thermo-throttles. A simple switch boa-d was used to independently open and close the various XFCU sole.noid valves. Duc to the physical separation of the control room and the vacuum chamber, roughly 8 m of 20 gage wire was used to connect the power supplies 10 the XFCU. The resistance of the wiring was measured at 0.6 -0.7 Ω which added to the roughly 0.2 Ω of throttle resistance.

C. Results

XFCU Acceptance Tests

During the first set of tests, the XFCU, although connected to the thruster, was operated with the thruster off. These measurements focused on the determination of the flow rates through the various flow paths though the unit, and their dependence on throttle current, XFCU inlet (plenum) pressure and ambient temperature. Performing these tests without simultaneous thruster operation simplified the, conduction of these tests and allowed a wider range of the XFCU performance parameters to be tested.

Figure 21 shows the pressure dependence of various flows and combination of flows through branch Al/K 1 of the unit.These data indicate that for the. specified inlet (plenum) pressure of 0.202 M Pa (29.2 psia), the anode flow rate is around 7.6 mg/s and the cathode flow rate is almost 0.7 mg/s (compared to the required values of about 5 mg/s and 0.3 - 0.4 mg/s, respectively. The cathode flow rate was found to be too high for operat ion at the design XFCU inlet pressure. Ideal cathode flow rates for the T-100 thruster at nominal operating conditions are 0.3 -0.4 mg/s. Similarly, Lhc anode flow rate was found too high. Anode flow rates required to maintain the discharge current at its desired value of 4.5 A usually arc found around 4.8 -5.0 mg/s. This problem was subsequently corrected in future XFCU units built at NIITP by appropriately sizing the length of tubing acting as flow restrictors in the respective lines of the XFCU.

In the case of the anode flow, however, a sufficiently high throttle current is able to lower the anode flow rate to the desired values even at the 0.202 MPa inlet pressure value. As shown in Fig. 22, a throttle current slightly greater than 2.5 A is required at the design pressure to maintain the correct anode flow rate. The design val uc for the throttle current at the nominal operating condition was originally specified at approximately 1.5 A, For a throttle currentof 1.S A, Fig. 22 shows that the inlet pressure to the XFCU would have to bc lowered to around 0.172 MPa (25 psia) for this unit.

Figure 23 shows the behavior of cathode flow vs. inlet (plenum) pressure for OA throttle current and for the required value for nominal operating conditions of the thruster (2.5 A). Note that the thermo-throttle dots not act directly on the cathode flow since it is placed only in the anode. flow lines. As Fig. 23 shows, the cathode flow tends to drop slightly at higher throttle currents. This can likely bc attributed 10 a warming-up effect of the XFCU unit duc to heat dissipation in the throttle. This effect, however, is significant at the 0.202 Mt'a design operating condition of the unit and is around a 0.1 mg/s reduction in flow. It is unclear what this value would bc for a redesigned unit which delivers 0.3 -0.4 mg/s cathode flow at 0.202 MPa inlet pressure.

Another interesting and so far unexplained phenomenon was noted when comparing the combined anode and cathode flow measured at 2.5 A throttle current with the individually measured flow rates for anode and cathode. As Fig. 26 shows, the cathode flow rate that has been computed by subtracting the measured anode flow rate at 2.5 A throttle current from the corresponding measured combined anode and cathode flow rates is larger than the measured cathode flow rate when the throttle current was set to 2.5 A. This behavior was found to bc repeatable. Onc possible explanation is that a leak developed somewhere in the cathode flow line at elevated temperatures caused by the thcrmo-throttle. This explanation, however, is purely speculative at this point. It should be noted, however, that no discrepancy was found between these flow rate.s at OA throttle current as Fig. 21 demonstrates. The corresponding flow rates, calculated from the curve fits to the data of Fig. 21 are listed in ~'able III and, as can bc seen, add up almost perfectl y. Small remaining differences may bc real or may bc attributed to inaccuracies in the flow measurement.

The temperature sensitivity of the various flow rates was investigated further by cooling the XFCU as described above and operating the unit at various temperatures ranging from 2.6 C to 32 C. Figures 24 and 25 show the results for the anode and cathode flows of branch A 1/K 1. Similar results were obtained for the corresponding flows of branch A2/K2. The curve featuring sol id symbols were taken at a previous test run. For each curve a temperature range is given because XFCU temperat urcs changed rapidly during the data recording as heal dissipated by the opened solenoid valves raised the XFCU temperature. The cooling loop set-up described above was not able to maintain the XFCU at the low temperature when the XFCU was operating.

According to the curve fits given in Fig. 24, anode flow rates drop from 8.8 mg/s LO 7.6 mg/s as the. temperature increases from about 2-4 C to 30-32C at 0.202 MPa (29.2 psia) inlet pressure, corresponding to a 13 % drop in flow rate or about 0.04 mg/s pcr degree C. At lower pressures the corresponding flow rate differences are 14% or 0.03 mg/s pcr degree C at 0.172 Mf'a (25 psia) and 16% or 0,02 mg/s per degree C at 0.138 MPa (20 psia). These arc sizable mass flow rate changes that will have to be taken into account when designing the thermal-control subsystem for a flight unit.

As can be seen in Fig. 2S, cathode flow rates do not seem to vary as predictably with temperature as anode flow rates do. This may be a real effect or, more likely, may be duc 10 the. increased difficulty of measuring the much smaller cathode flow rates with the same relative accuracy as the larger anode flow rates. Nonetheless, the same trend as observed for the anode flow rates is also visible in Fig. 25 in that flow rates drop as temperature of the XFCU increases. Here, at 0.202 MPa (29.2 psia or 2 atm) inlet pressure, the cathode flow rate drops from 0.76 mg/s to 0.7 mg/s or by 8%, corresponding to a flow rate drop of about 0.002 mg/s pcr degree C. At 0.172 MPa (25 psia) inlet pressure the corresponding flow rate drop is 9.7 % or 0.002 mg/s per degree C and at 0.138 MPa (20 psia) this drop is found to be 9.7 % or 0.001 mg/s per degree C. Although the cathode flow rates arc too high at the design XFCU inlet pressure for this particular unit as was pointed out before, the cathode flow rate changes appear acceptable.

Final I y, flow rate transients were measured to determine the time it takes to complete the flow rate changes when turning the thermo-throttle on or off. Here the thcrmo-throttle current was set to 2.5 A to operate this particular XFCU unit at the required anode flow rate of about 5 mg/s. Figure 26 indicates that the dc.sired flow rate can be achieved within about three minutes after turning the throttle on. Similarly, it takes about three minutes to return the flow rate to its original cold flow condition when the throttle is turned off, as shown in Fig. 27.

XFCU/T-100 integration Tests

Following the tests without thruster operation, the XFC unit was tested with the T-100 operating. Here, of particular interest were the impact of throttle current on discharge current via mass flow rate changes and temperature effects on the X FCU and their influence on thruster performance.

Figure 31 shows the relationship between discharge current and throttle current. As can be seen, roughly 2.5-2,6 A throttle current arc required to maintain the desired beam current of 4.5 A for this particular XFC unit which is consistent with the. value determined by measuring the anode flow rate sensitivity to throttle current as discussed above. A change in throttle current of 1 A will effect a change in discharge current of about 1.5 A for an inlet pressure of 0.202 MPa (29.2 psia). At about 0.172 MPa (25 psia), the effect changes in throttle current have on beam current arc less pronounced. Here, a 1 A-change in throttle current only results in a 1.2 A change. in beam current. As Fig. 29 indicates, the change in discharge current is entirely due. to a change in mass flow rate, since the slopes of both mass flow rate. and discharge current curves arc virtuall y identical, in particular for the case of 0.202 MPa (29.2 psia) pressure where the impact of the almost constant cathode flow rate on total flow rate is tcss pronounce.d (the slopes can easily be take.n from the mathematical curve fit expressions listed in Fig. 29).

Figure 33 shows how much electrical power is required to maintain the required mass flow rates. As can be seen, about 5.5 W arc required 10 maintain the correct discharge flow with this XFC unit. It should be pointed out, however, that the long wiring required to connect the XFCU to the power supplies in this set-up significantly increased the power requirements. Resistance of the X FCU throttle circuit increased by about 0.7 Ω duc to the longer wire. If power suppl ics could be placed closer to the XFCU, eliminating long wiring, these power requirements may be reduced to almost 20% of the measured value in this set-up, or about 1.2 Watt. This value is very small in comparison to the power dissipated in the thruster and demonstrates a highly efficient design. Note also, that this particular XFCU required higher throttle currents than usual to maintain the correct flow at the specified design pressure of 0.202 MPa (2 atm). If flow restrictors and thcrmo-throttles were, redesigned resulting in lower throttle currents, the throttle power requirements could be reduced further by a significant amount. If by proper design of the flow restrictors and throttles the throttle current could be lower to the original design value. of 1.5 A, power requirements would further drop by almost a factor of three, or to about 0.4 - 0.5 Watt.

As with the X FC unit alone, temperat urc sensitivity tests were performed during the integrated XFCU/T-100 tests. In the tests described in the following paragraphs, only the XFCU was cooled while the T-100 allowed to operate at its usual operat i ng temperat urc when placed in a room temperature environment (typically around 230 'C). Using this approach, temperatu re effects on the XFCU could be easily isolated. Figure 28 shows the impact on thruster operation as expressed by the discharge current. Sine.c elevated XFCU temperature and throttle current both increase xenon viscosity, thus lower xenon flow, less throttle current is required at elevated XFCU temperatures to maintain the 1'-100 nominal flow condition. For 4.S A twain current, the throttle current can be reduce by 0.3 A from 2.9A at 14 C to 2.6 A at 32 C. At higher beam currents of 4.9 A the change is 0.3 A also from 2,6 A to 2.3 A, At a lower beam current of 4.1 A the change is 0.4 A from 3.2 A at 14 C to 2.8A at 32 C. As mentioned, these temperature effects arc fairly sizable and should be taken into account when designing the thermal control subsystem for the X FCU/T- 100 flight environment.

Figure 32 shows the changes in total mass flow rate for varying throttle currents and the two different temperature conditions. Again, slopes for the beam currents of Fig. 31 and for the mass flow rate. of Fig. 32 arc virtually identical, demonstrating that changes in beam current with throttle current result from changes in total mass flow rate.

IV. Xenon Propellant Storage and Distribution System (1'S1)S) Evaluation

A. Description of PSDS and Components

The purpose of the PSDS is to feed propellant from a propellant tank into the XFCU at the appropriate flow rate and XFCU inlet pressure. The PSDS underwent many design reviews to fit the changing needs of the RHETT - 1 system, some occurring late in the program. The propellant tank was eliminated fairly early from the system since it is highly mission specific and the demonstration of pressurized xenon storage was not believed to be a necessary part of the RHETT-1 program which sought to demonstrate a "flight-type" Hall electric thruster system. The remaining system finally took on the form shown in Fig. 33, A schematic of the system is shown in Fig. 34. The s ystem was provided by Moog Space. Products.

The final design iteration consisted of a latch valve by Moog serving as the isolation valve of the system, a one-stage regulator, also by Moog, able to regulate xenon from an inlet pressure of 9.307 MPa (1350 psia) to an outlet pressure, set by the desired XFCU inlet pressure, of about 0,202 MPa (29 psia). The system featured two pressure transducers (high and low) by Paine, located upstream and downstream of the regulator and two fill and drain valves, again by Moog. In the last design iteration of the PSDS shown in Fig. 33, onc of the fill and drain valves is used in the unusual function as the inlet to the system. Typically, inlets to propellant feed systems usc welded joints, or, in the case of a laboratory model such as the system described here, usc Swagelok® or AN fittings. However, at the time the last design change to the PSDS was made, the fill and drain valves were already built and thus were used in the function described. The PSDS is mounted together with the XFCU on an aluminum mounting plate. The overall weight of the system components (excluding the. XFCU and mounting plate) is 996 gram.

The latch valve is bawd on an earlier design by Moog Space Products for the Pl uto Fast-Fl yby program and was modified for operation at higher pressures. The Maximum Expected Operating Pressure (MEOP) is 14.996 MPa (2175 psia) and the unit was proofed to 22.683 MI's (32.90 psia). The latch valve weighs 112 gram and features an internal propellant filter with an absolute filter rating of 5 micron. The valve has an

transducer installed both upstream and downstream of the. mass flow meter.

C. Results

The results of the pressure regulation tests arc shown in Table IV. As can be seen the pressure just upstream of the mass flow meter installed external to the PSDS, is within 1379 Pa (0.2 psia) between 0.198 MPa (28.72 psia) and 0.199 MPa (28.95 psia) for inlet pressures ranging from around 0.069 MPa (100 psia) to S.110 MPa (741.2 psia, max. xenon bottle pressure). The original specificat ion for the Moog regulator required the pressure to be maintained at 29 ± 1.0 psia (0,200 MPa ± 0.069 MPa) and was successfully achieved. Mass flow rates were maintained at 50,3 seem . 50.4 seem of xenon throughout these tests, corresponding to xenon flow rates encountered at nominal T-100 operation. 'i 'he PSDS was thus found to operate successfully and several PSDS components, including the regulator, were taken over into the. RHETT- 1 follow-on program, RHETT-2.

V. PSDS, XFCU and T-1OO-3 integrated Tests

The xenon propellant system, xenon flow control unit and T-1 00-3 were installed into the vacuum chamber and tested as an integrated system. A series of tests were performed to evaluate the system and are described below. Cathode #2 was used for the tests described below; cathode #1 was unavailable. No thrust measurements were obtained. The SPI cathode ignitor power supply was used in these tests to start the cathode.

A. Cold Cathode Starting

Since the NIITP cathode. has no tip heater, there was concern that the cathodes may not start at very cold temperatures. Experiments were performed to evaluate, ignition characteristics of the NIITP hollow cathode. A shroud cooled with liquid nitrogen was placed around the thruster body so that only the downstream face of the T-100-3 faced room-temperature. The other five sides of the thruster faced the LN2 shroud. The thruster was thermally isolated from the shroud. Thermocouples were attached 10 the pressure regulator, the T-100-3 body (side next to the. cathode anti the side 180 degrees from the. cathode) and to the thruster cathode near the thruster body. LN2 **was flowed** through the shroud until the cathode thermocouples indicated that the cathode was below two degrees C, and the thruster body was below 3.5 degrees C. The XFCU was used to supply xenon to the, cathode and was operated at room temperature during cold cathode ignition experiments. A laboratory propellant system was used to suppl y xenon to the X FCU for these, tests.

The cathode, with an indicated barrel temperature of less than 2 degrees C, was ignited at a flow rate of between 0.35-2 mg/s for ten starts without incident. Fifteen additional cathode starts were performed with the cathode flow at 2 mg/s, a cathode temperature as low a -23 degrees C and a thruster body temperature as low as -15 degrees C. The data indicate that the. 1'-100-3 heaterless cathode, when new, can be reliably started at temperatures as iow as -23 degrees C.

LN2 shroud temperature as a function of time after 'I'-1OO-3 start is shown in Fig. 36. Shroud temperature was initially approximately -140 degrees C (133 K) until the thruster was turd on, where.upon the shroud temperature increased to approximately 153 K. Cathode barrel temperature data arc shown in Fig. 36. The data indicate that the thruster cathode barrel achieved a steady-stale temperature of about 220 degrees C approximately 200 minutes after the thruster was turned on,

B. Cold Pressure Regulator Tests

Experiments were performed to measure PSDS pressure regulator performance as a function of regulator temperature. Thermocouples were attached to the pressure regulator and to the PSDS plate. The flow rate was controlled using the XFCU and propellant was exhausted through the thruster. Xenon feed pressure into the pressure. regulator was approximately **5,540** kPa (804 PSIA). The data for this test arc summarized in Fig. 37, The data indicate that with a base plate temperature of -24.8 degrees C, a regulator temperature of 21 degrees C, and a feed pressure of 803 PSI A there. arc no n ieasurable variations in the regulated pressure. Some variations in regulated pressure were observed at regulator temperatures below 20 degrees C. Significant variations in regulated pressure occurred on] y at regulator temperatures below 5 degrees C. At a regulator temperature of O degrees C, variations in regulated pressure, occurred at feed pressures above 340.7 PSIA. High pressure transducer output voltage as a function of temperature is shown in Fig. 38. The pressure transducer output was stable over the temperature range tested.

C. Integrated System Testing

The PSDS, XFCU and T-100-3 were placed in the vacuum chamber and tested together as an integrated subsystem. First, a pressure rate-of-rise test was conducted to verify that no part of the PSDS and XFCU leaked. The pressure rate-of-rise tests were performed with the valve to the PSDS closed, the XFCU supply valves open, and the X FCU cathode/antic valves closed; leakage anywhere in the trapped vohrmc between the supply line to the PSDS and the X FCU valves would be revealed via pressure decay in the trapped volume. At a feed pressure of 5,518.4 kPa (800.0 PSIA), a maximum leak rate of 0.008 seem was calculated. The resolution of this test was limited by the amount of time for the. pressure decay test (approximately 18 hours), and it is possible that the leak rate could be Icss than reported herein.

The PSDS was supplied with xenon al a regulated pressure of 5,S41 kPa (804 PSIA); the PSDS

supplied xenon to the XFCU at a regulated pressure that depended on regulator temperature. At the nominal conditions of 300 V and 4.5 A and a regulator temperature above 21 degrees C the discharge flow rate and thruster discharge were stable. Regulated pressure did not vary by more than plus/minus 0.01 PSIA over the test. once thermal equilibrium was achieved, there were no observable variations in thruster flow rate or discharge current, The XFCU worked very well with the PSDS and the T-100-3 and provided excellent discharge and cathode, flow rate control, With the XFCU controlling the engine mass ffow rates a variation in the discharge current of ± 7 mA (out of a total of approximately 4,5 A) was easily achieved. After reaching thermal equilibrium it was not necessary to adjust the XFCU current settings to maintain a constant discharge current unless the feed pressure changed. The NIITP thermothrottle provides much better flow rate/discharge current control than usc of micrometer valves.

Data for the integrated subsystem testing in vacuum are summarized in Table V. Subsequently the PSDS, XFCU and T-1OO-3 were integrated into the RHETT- 1 propulsion system and tested at LeRC. All subsystems performed nominally and arc di SC ussed in Ref. 26.

CONC1.US1ONS

A 1'-100-3 Russian Hall plasma thruster, flow control unit and US xenon propellant subsystem developed for the RHETT-1 propulsion system were evaluated for the RHETT- 1 propulsion system. The thruster evaluation program included performance testing at various discharge voltage and input power levels, and a 632-hour wear test. Thrust and efficiency of the T-100-3 are comparable to the SPT- 100. The. endurance test was performed for 349 on/off cycles and 632.4 hours of operation at an input power to the thruster of approximately 1.35 kW. Each cycle was nominally 24 hours of thruster on-time and ten minutes of thruster off-time. Thrust and thruster efficiency decreased, from 83 mN and 49% at 1301. to 81.5 mN and 45% at the completion of the wear test. Thruster mass decreased by approximatel y 20 g over 630 hours. over the course of the wear test the peak beam current density in the thruster plume measured on the thruster centerline decreased on] y slightly. T- 100-3 plume characteristics arc similar to those measured on the SPT- 100. Inner insulat or wear rates were a factor of three lower and outer insulator wear rates at certain locations were 30% greater than the insulator wear rates measured on the SPT-100. Life estimates for the T-100-3 based on the wear test data arc consistent with life estimates of the SPT- 100.

A Russian-designed and fabricated laboratory xenon flow control unit was evaluated over a range of XFCU temperatures, input pressures, and flow rates. The XFCU as tested featured a design error in that it was not able to deliver the proper flow rates at the specified inlet pressure of 0.202 MPa (2 atm). This error, however, can easily be corrected by sizing the tubing length of the flow restrictors and thermo throttles properly and this design change has alread y been incorporated in the construction of further XFC units at NIITP. Apart from this, the XFCU performed very satisfactory. The response lime was relatively fast for a thermally controlled unit and mass flows could be easily and precisely controlled. A clear dependency of the various flow rates on ambient temperature was found which has to be accounted for when designing the thermal control subsystem for a flight unit.

T "he, propellant s ystem includes a pressure regulator, on/off valves, service valve and high/flow pressure transducers, built 10 flight-like standards and assembled onto a mounting plate structure. The propellant system mass was 509 g. Testing of the propellant system included experiments to measure output pressure regulation variations through a temperature range of -20 through + 30 degrees C with an input pressure range of 414-6100 kPa (60-885 PSIA). The PSDS performed very well during JPL acceptance tests; all design specifications were met. The regulator performed exceptionally well, able to regulate xenon up to 9.308 MPa (1350 psia) inlet pressure to the desired outlet pressure of ().2()2. MPa (29.2 psia). II's small size and weight were accomplished by using a single stage regulator design, despite the large ratio of inlet 10 outlet pressure.

The flight-l ikc propellant feed system, T-100-3 thruster, and laboratory xenon flow cent rol unit were tested together as a system in vacuum; all subsystems functioned nominally. The thruster, XFCU and XPS then were subsequentl y integrated into the RHETT-1 propulsion system at NASA Lewis Research Center and tested with a power processing unit and integrated structure.

ACKNOWLEDGMENT '

The authors thank Mr. Alison Owens and Mr. Robert Toomath for their efforts in support of the testing described in this paper. The authors grate.fully acknowledge the support of Dr. Len Caven y, Innovative Science and Technology office of the Ballistic Missile Defense Organization, and Joe Wetch of Space l'owcr, inc., San Jose, California.

The work described in this paper was perfomed by the Jet Propulsion Laboratory, California Institute of Technology, and was sponsored by the Ballistic Defense Missile Organization/Innovative Science and Technology, through an agreement with the National Aeronautics and Space Administration.

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Table 1. T-1OO-3 Performance Characteristics Measured at JPL. Data for the T-1OO-3 #1 1 are beginning of life (1101.),

2'-100 Desig.	Cycles	Testing at JPL (Hrs)	Discharge Voltage (v)	Discharge Current (A)	Discharge. Flow* (mg/s)	Cathode Flow (mg/s)	Magnet Power (w)	Thrust* (mN)	Thruster Efficiency*
#lo	1-20	14.0	299.7	4.52	4.8	0.36	36	82.4	0.48
#/l]	25	7.1	300	4.49	4.77	0.35	28	81.3	0.47
#11	30	7.1	200	4.52	4.81	0.37	24	62.0	0.41
#11	35	7.1	301	4.00	4.29	0.36	18	72.6	0.46

* Not corrected for backflow of facility xenon into the thruster
* -1.4 mN was added to measured thrust to include cold gas thrust component, as discussed in the Apparatus section of this paper

Table II. 1'-100-3 Wear test Significant Events

Cycle	Total* Thruster Hours	Description
21-35	27.1	3'-100-3 # 11 characterization and DAC system check
36	27.1	Wear test started
37	65.6	Discharge current increases during first fcw minutes after start-up
38	76.4	Computer shutdown, LVDT exceeded lower limit duc 10 thrust stand inclination failure
39	76.4	First observation of flickering, unstable plume; manual shutdown because of insufficient discharge flow rate
41	99.0	No thruster start at S00 V, 20 mA
42	141.6	Turned off cryopumps to remove helium from facil ity
43	141.6	Sparks from discharge chamber on start-up
44	185.1	Changed xenon bottles
48	256.6	Ignitor supply capacitor failure, manually turned off thruster
53	360.5	Significant wear in cathode. # 1 observable
55	396.8	Computer shutdown duc to power grid surge
56	416.5	Computer shutdown duc to iow discharge flow rate
61	534.2,	No thruster start at 500 V, 20 mA; computer shutdown duc to power grid surge
62	576.0	No thruster start at 500 V, 20 mA; computer shutdown due. to floating potential exceeded lower limit
69	651.5	12s1 wear test cycle
70-88	665	T-1OO-3 characterization at JPL and LeRC

* Includes approximately 20 hours of operation at NITP

Table I I: Comparison of XFCU Flow rates at OA Throttle Current

Pressure (MPa)	Anode Flow (mg/s)	Cathode Flow (mg/s)	Cathode Start Flow (mg/s)	Measured Anode+Cathode (mg/s)	Measured Anode.+Cathodc + Cathode Start (mg/s)
O.138 (20 psia)	3.72	0.36	1.26	4.07	5 . 4 7
0.172 (25 Psia)	5.82	0,52	1.79	6.36	8.15
0.202 (29.2 psia)	7.64	0.68	2.31	8.28	10.21

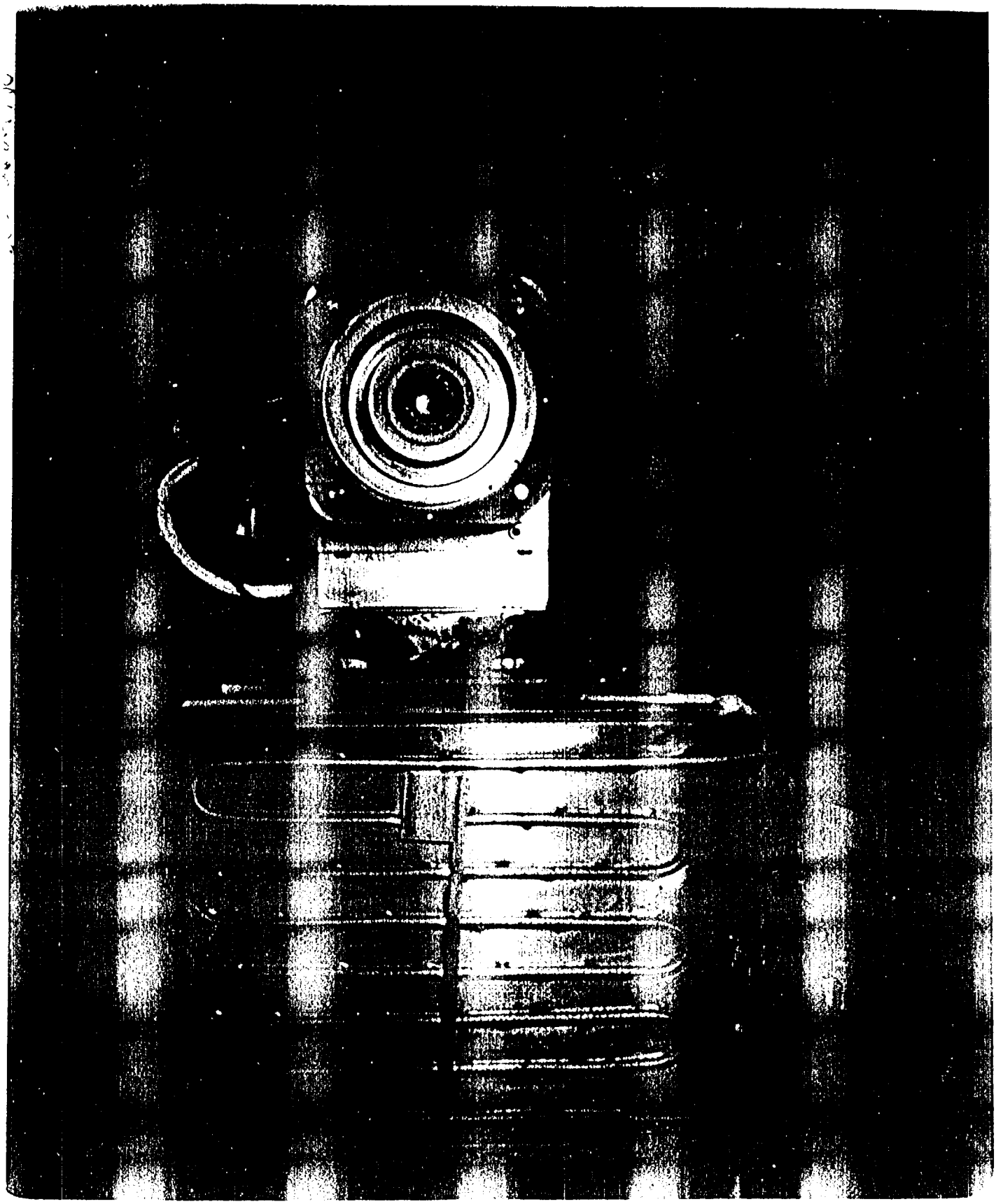
Table 1 V: Results of PSDS Acceptance Tests at JPL

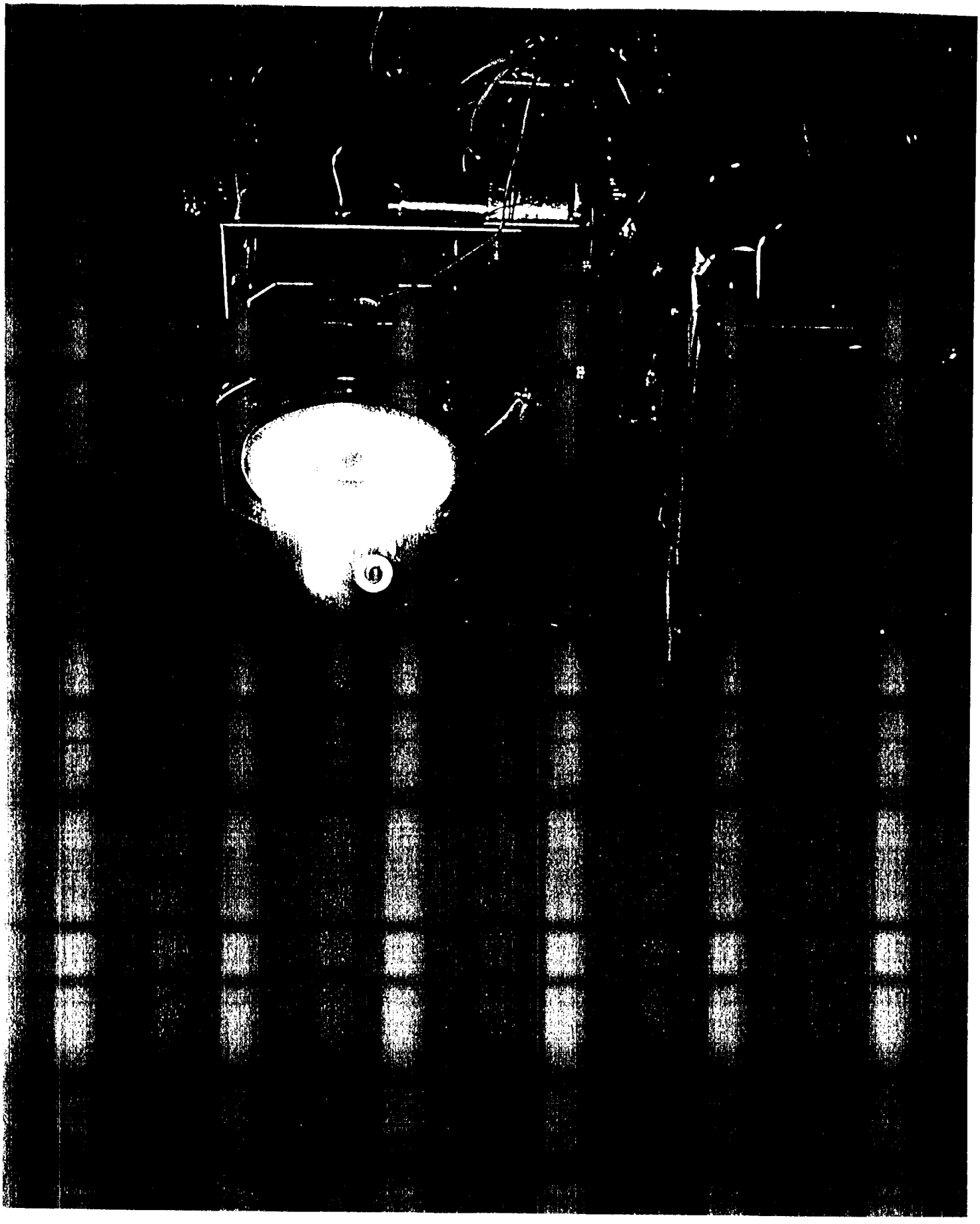
Feed Pressure (psia)	Pressure upstream of Flowmeter (psia)	Pressure Downstream of Flowmeter (psia)	PSDS 1 ow Pressure transducer (psia)	Mass Flow Rate (seem)
93.8 -101.1	**28.72-28.73**	**28.33**	###	**50.3**
32.1 .5-321,7	28.83-28.84	28.43	###	50.5
499.0-499,1	28.86-28.87	28.46	###	50.3
645.9	28.82	28.52	###	50.4
646.2	28.82	28.52	###	50.4
741.2	28.95	28.54	###	50.4

Table V. Integrated Test Data

Thruster Voltage (V)	Discharge Current (A)	Total Flow Rate (mg/s)	Regulated Pressure psia) (V)*	Thermothrottle (A) (V)
297.5	4.49	5.7	28,7 1.43	**2..0 2.35**

* Pressure regulator output voltage





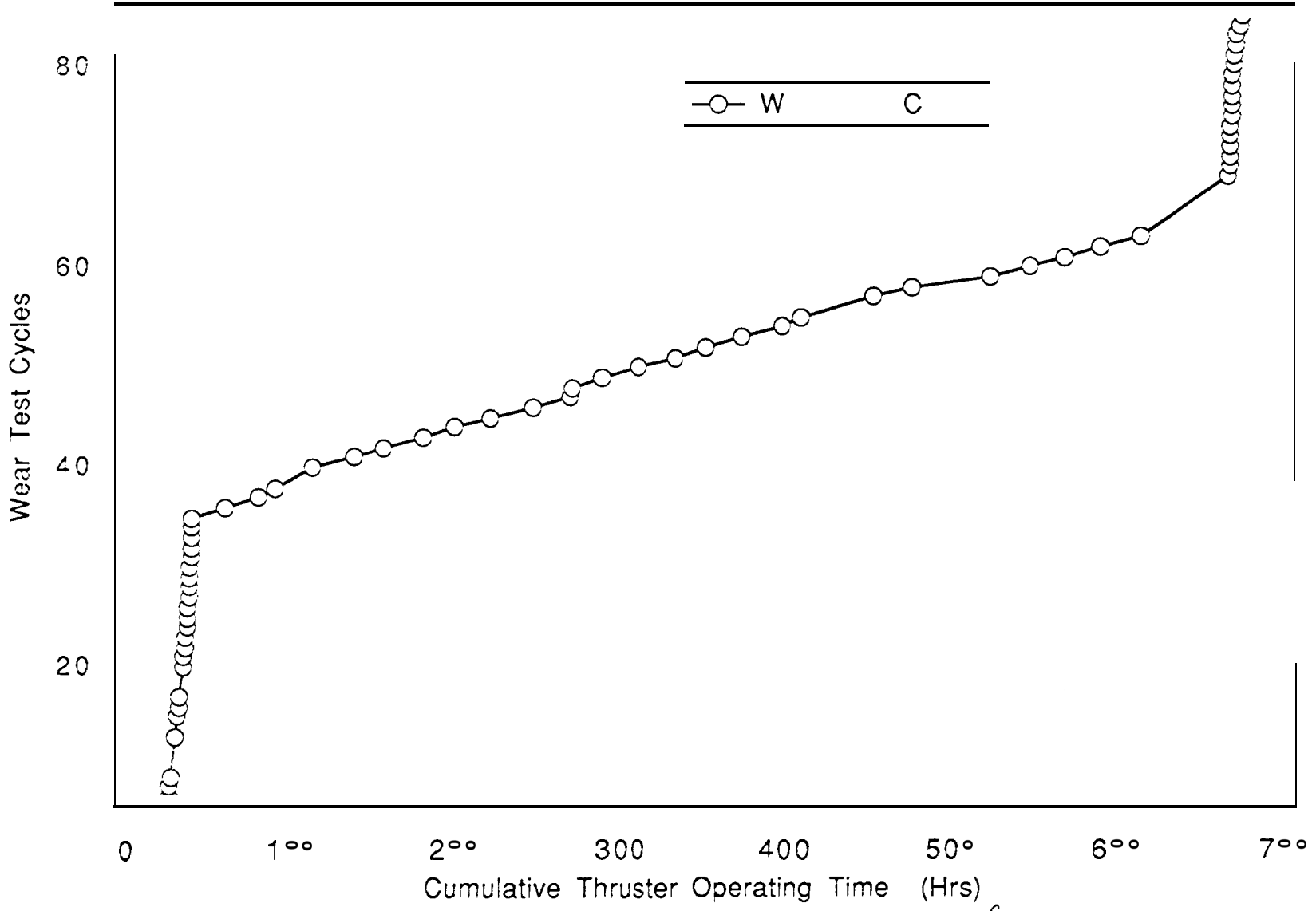
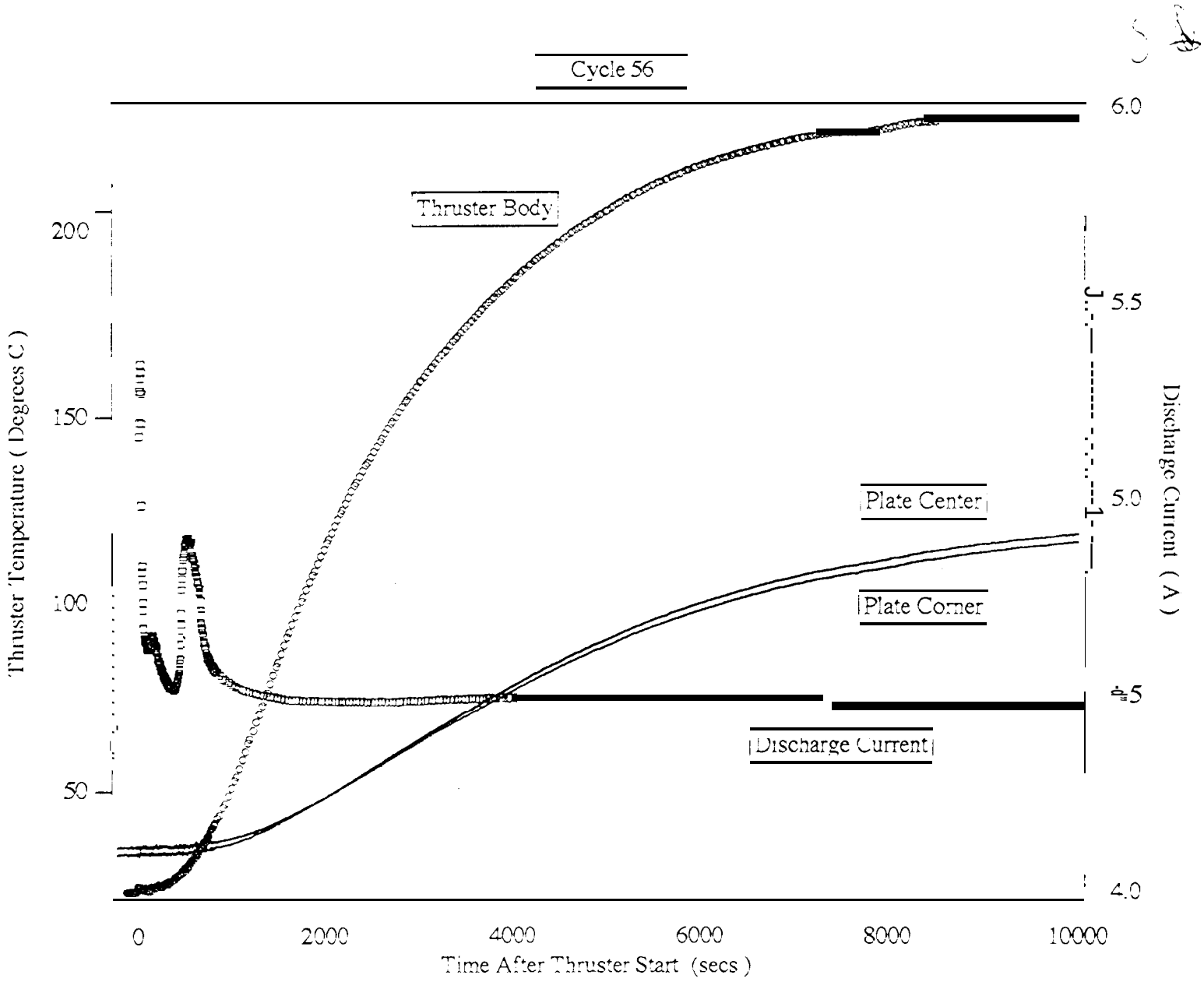
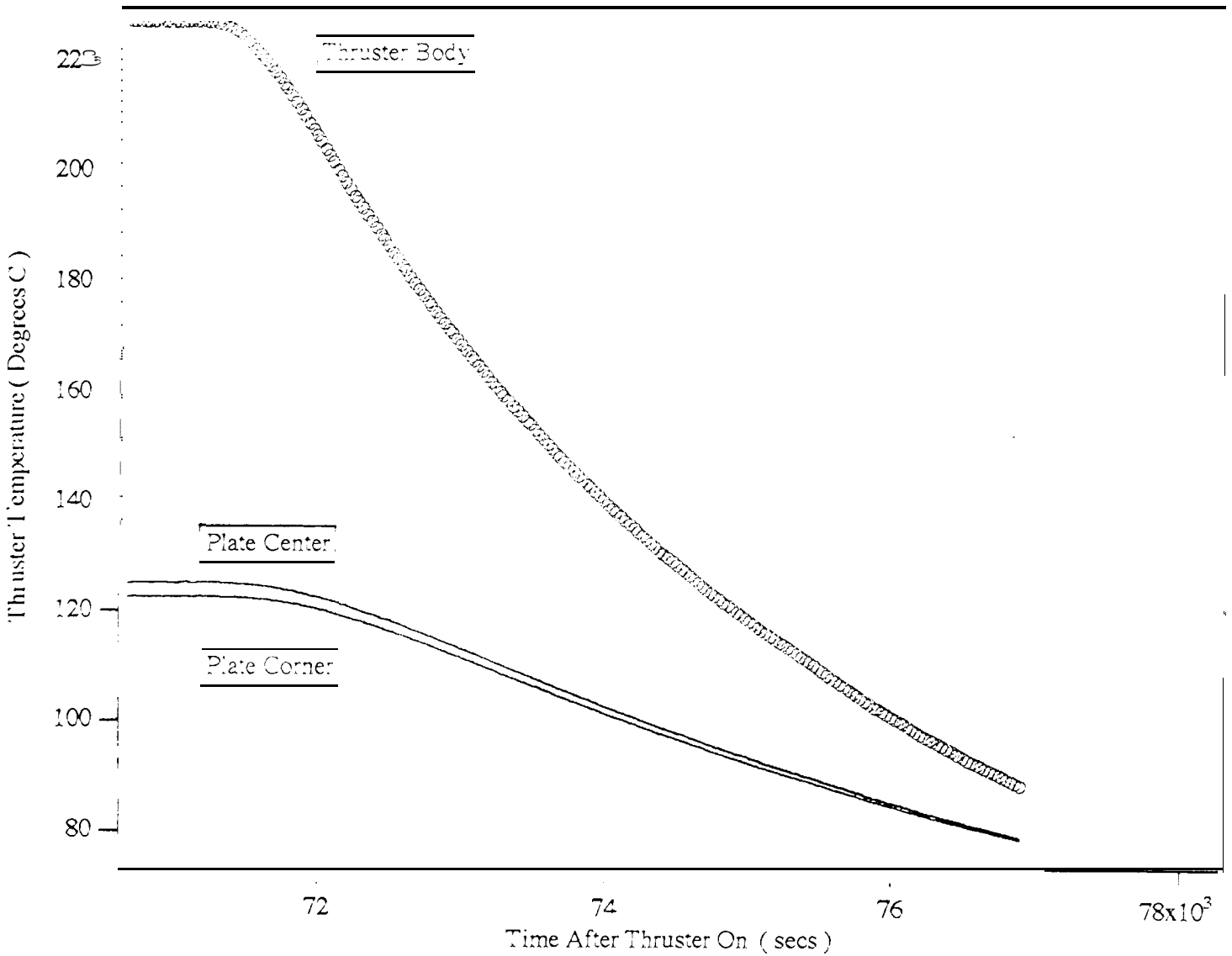

80
60
40
20
Wear Test Cycles
W
C
0
1°°
2°°
300
400
50°
6°°
7°°
Cumulative Thruster Operating Time (Hrs)

Fig 4



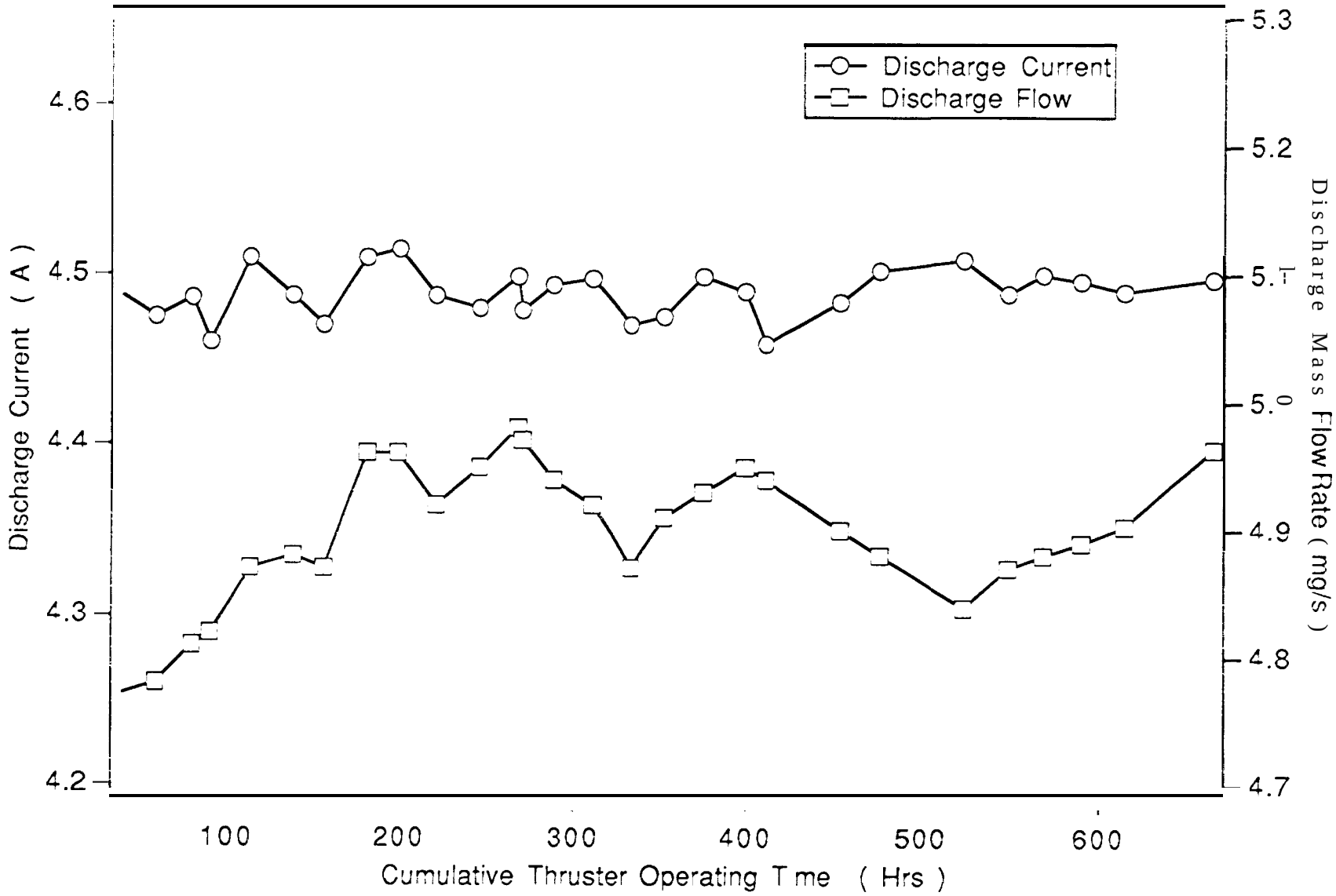
Which Thruster?

Cycle 56



Where is "Thruster Off" command?

Which thruster?



Which Thruster ?

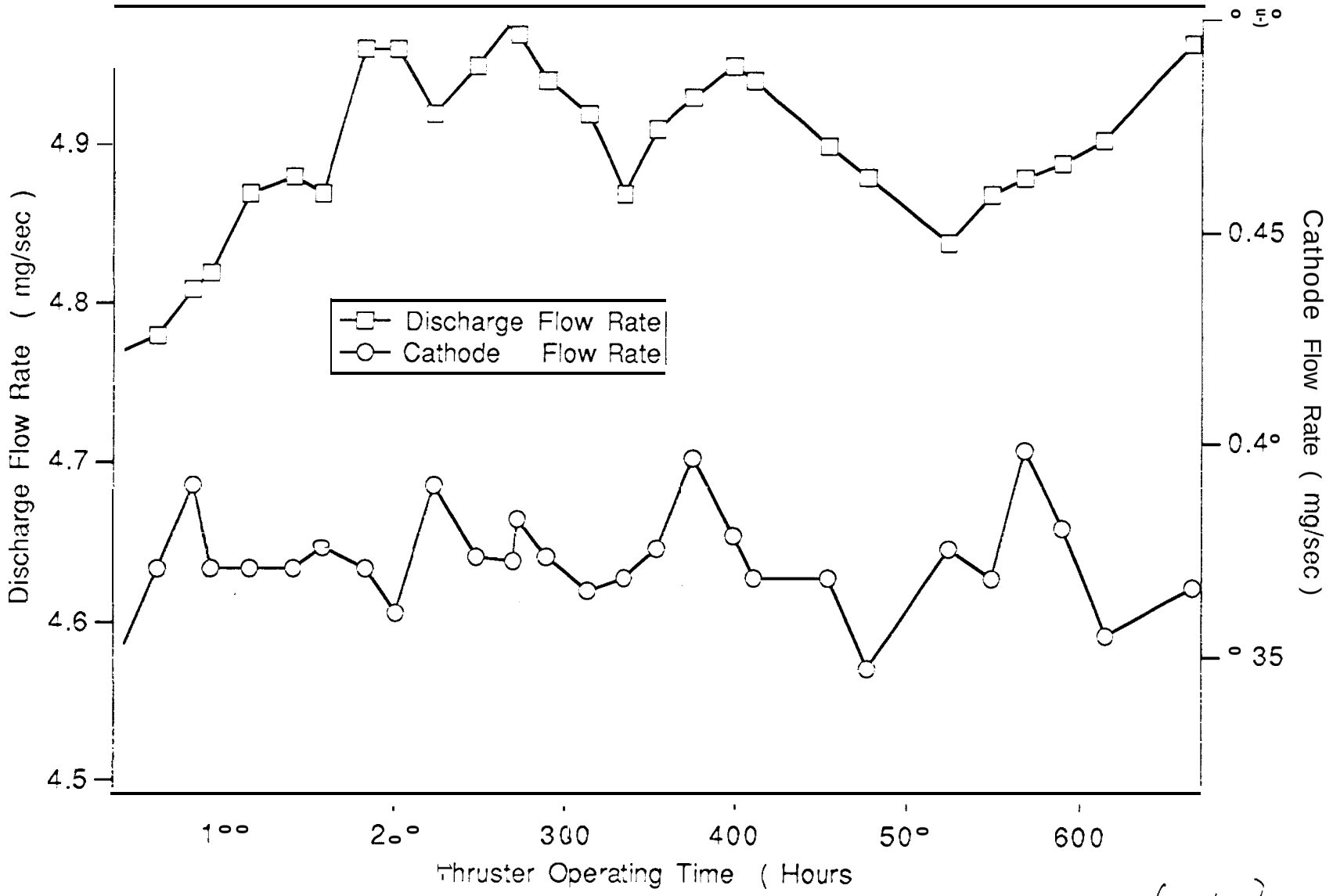
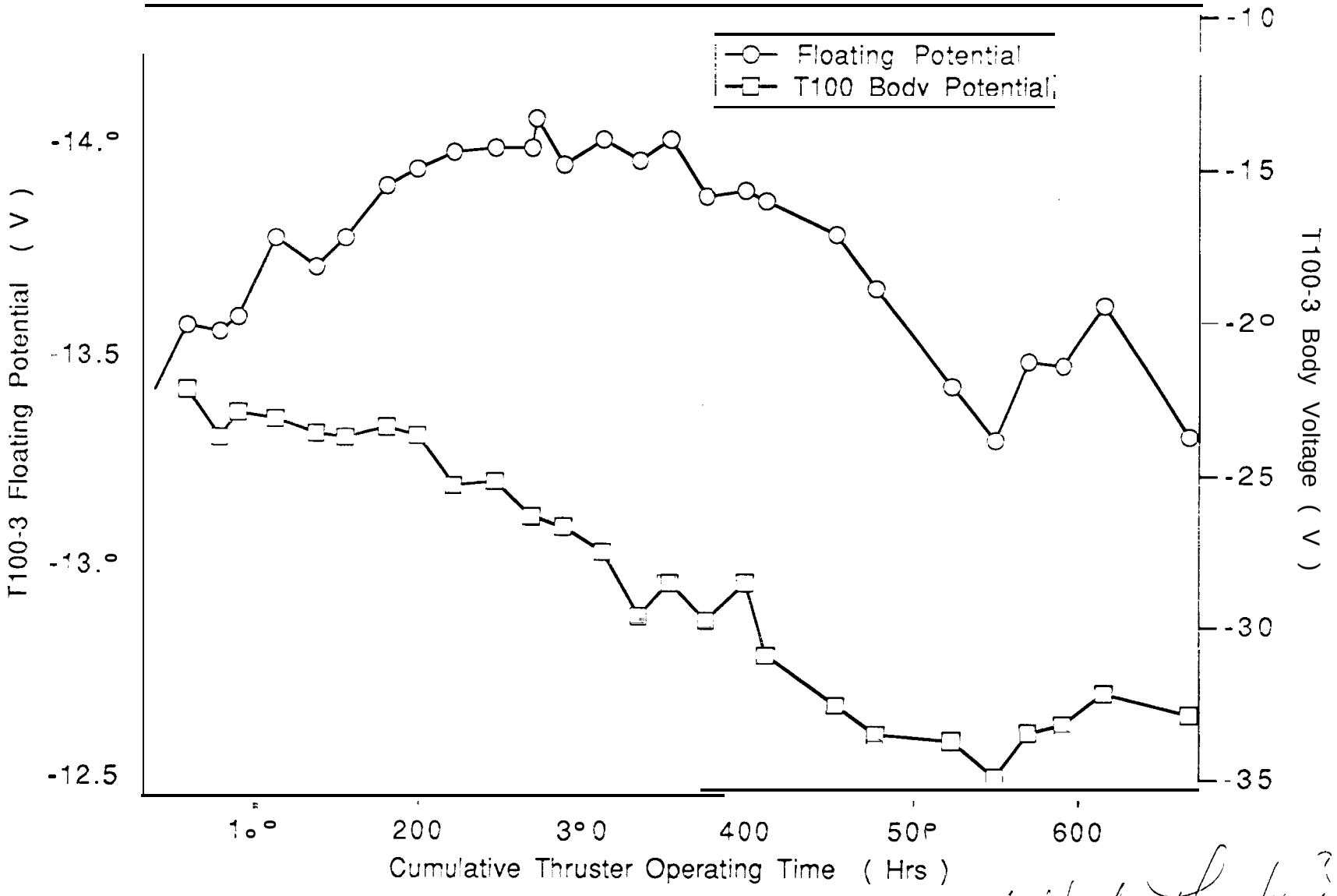
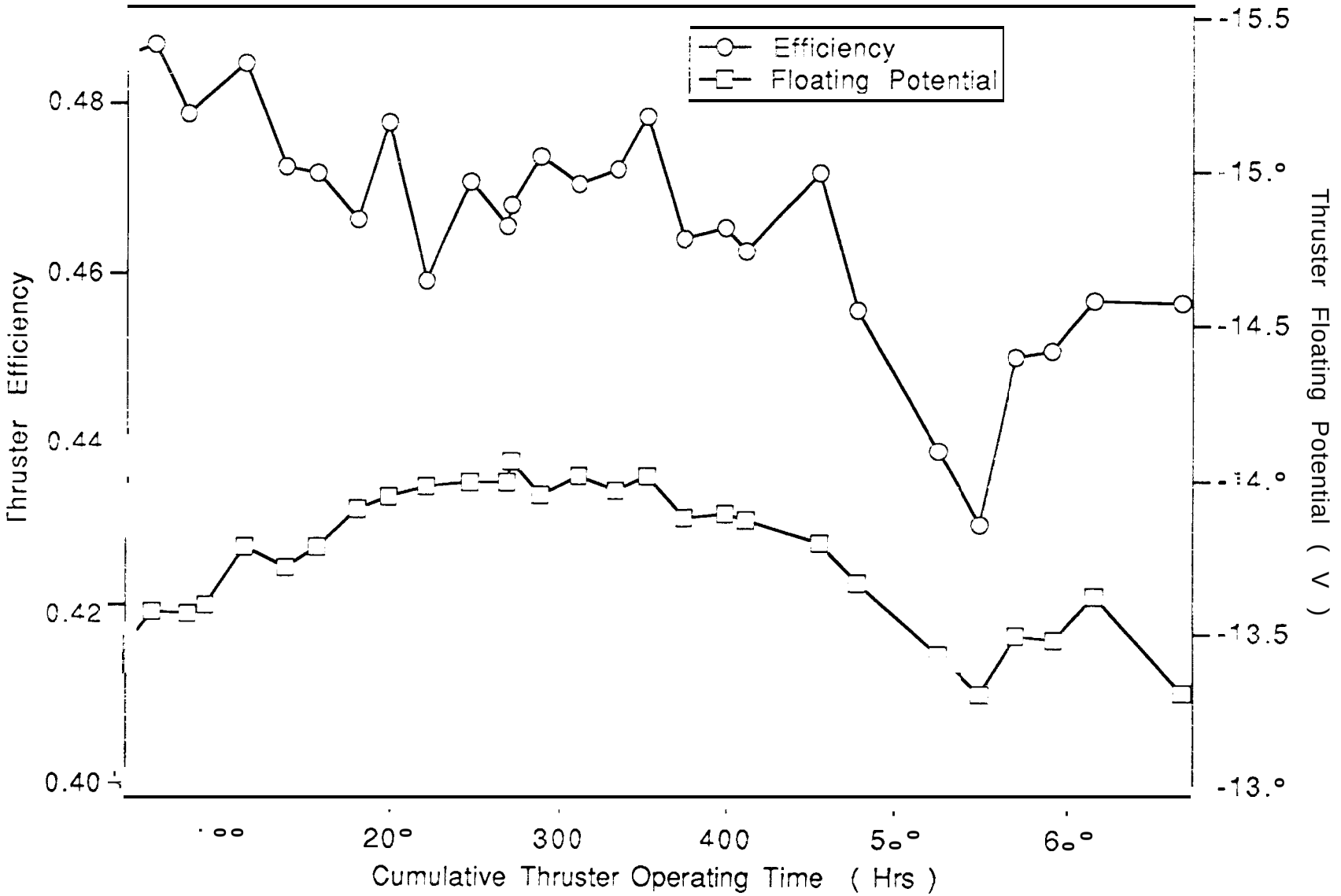


Fig 8

Which Thruster?



Which Thruste ?



Which Thruster?

Which Thruster

Fig 11

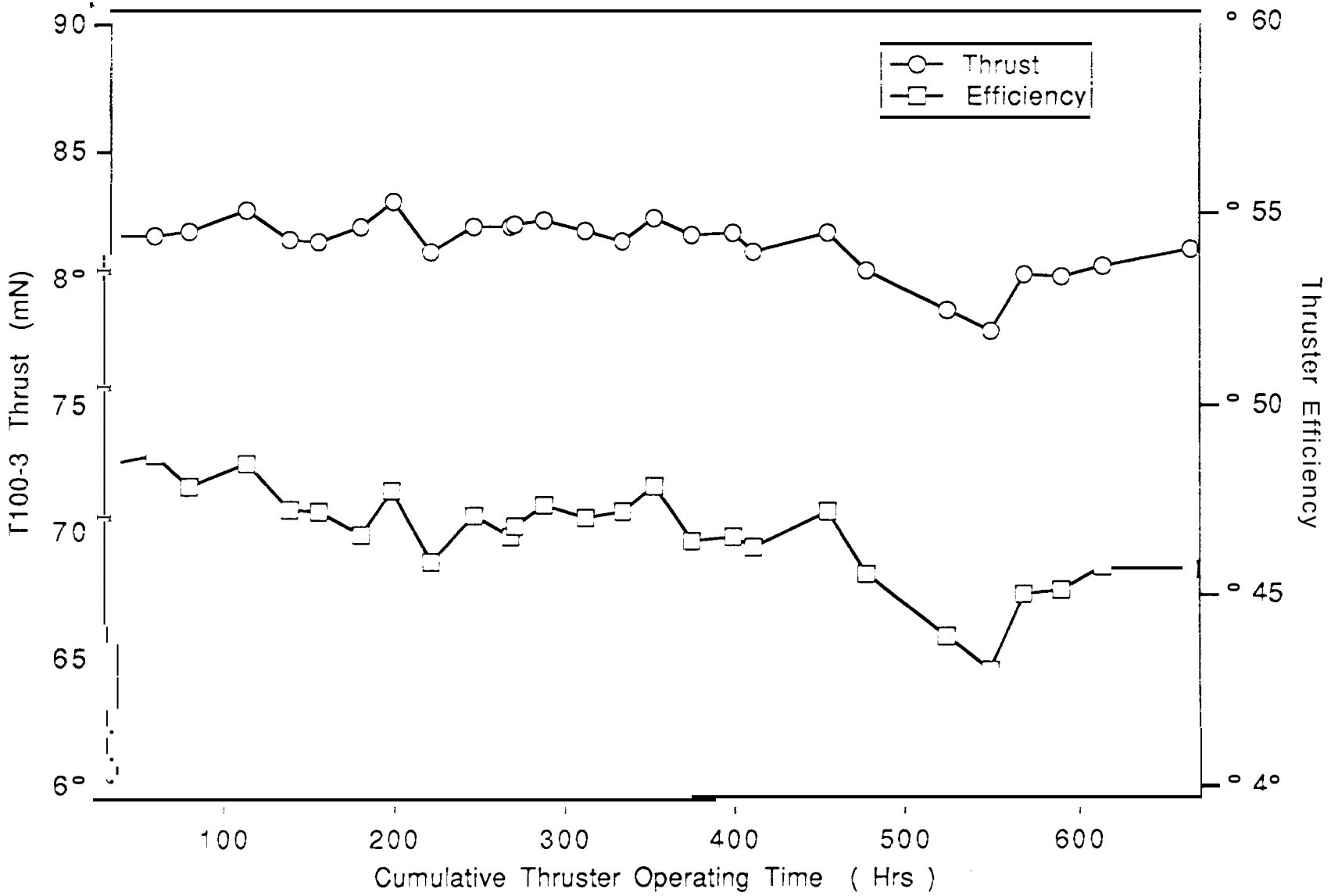
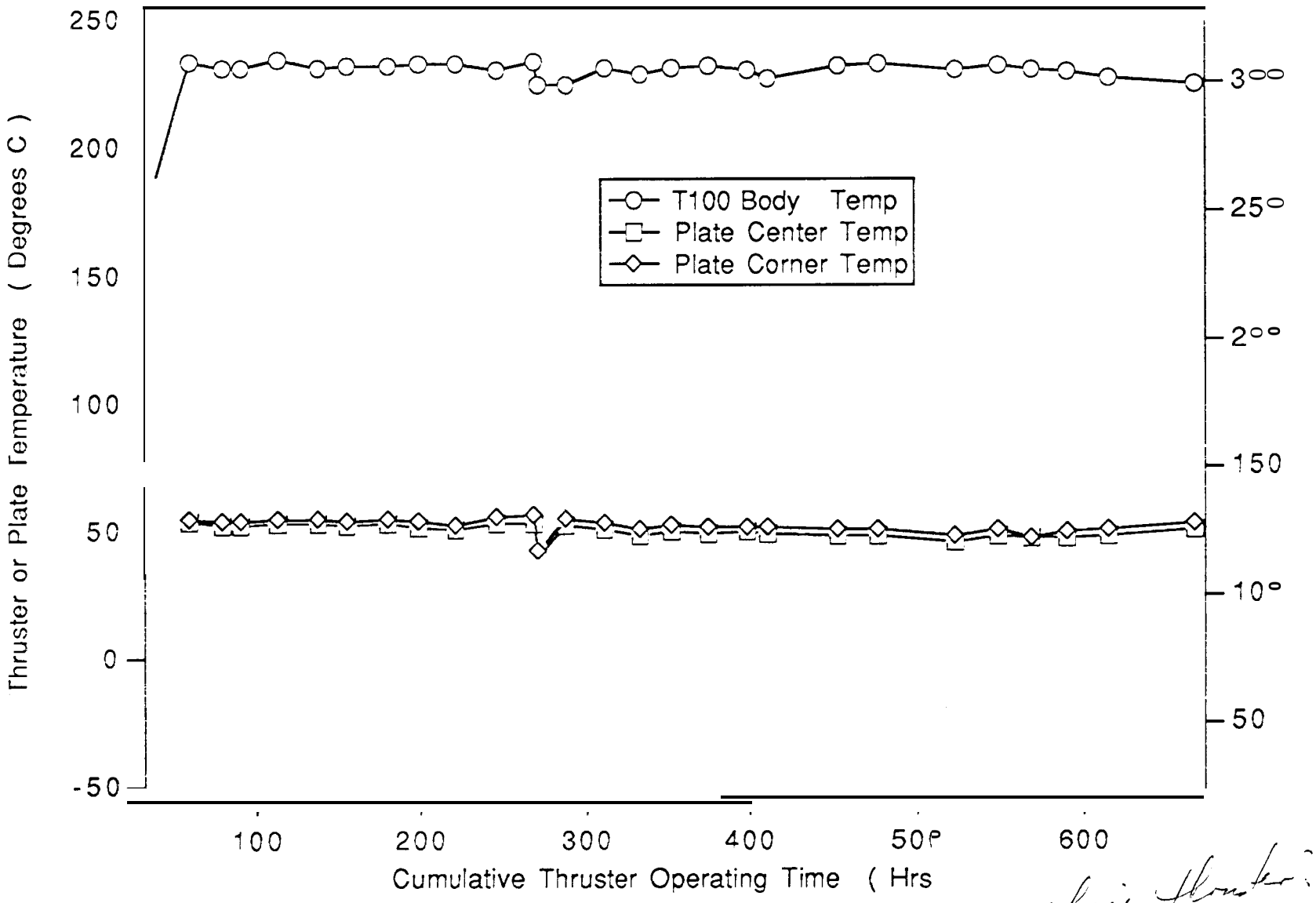
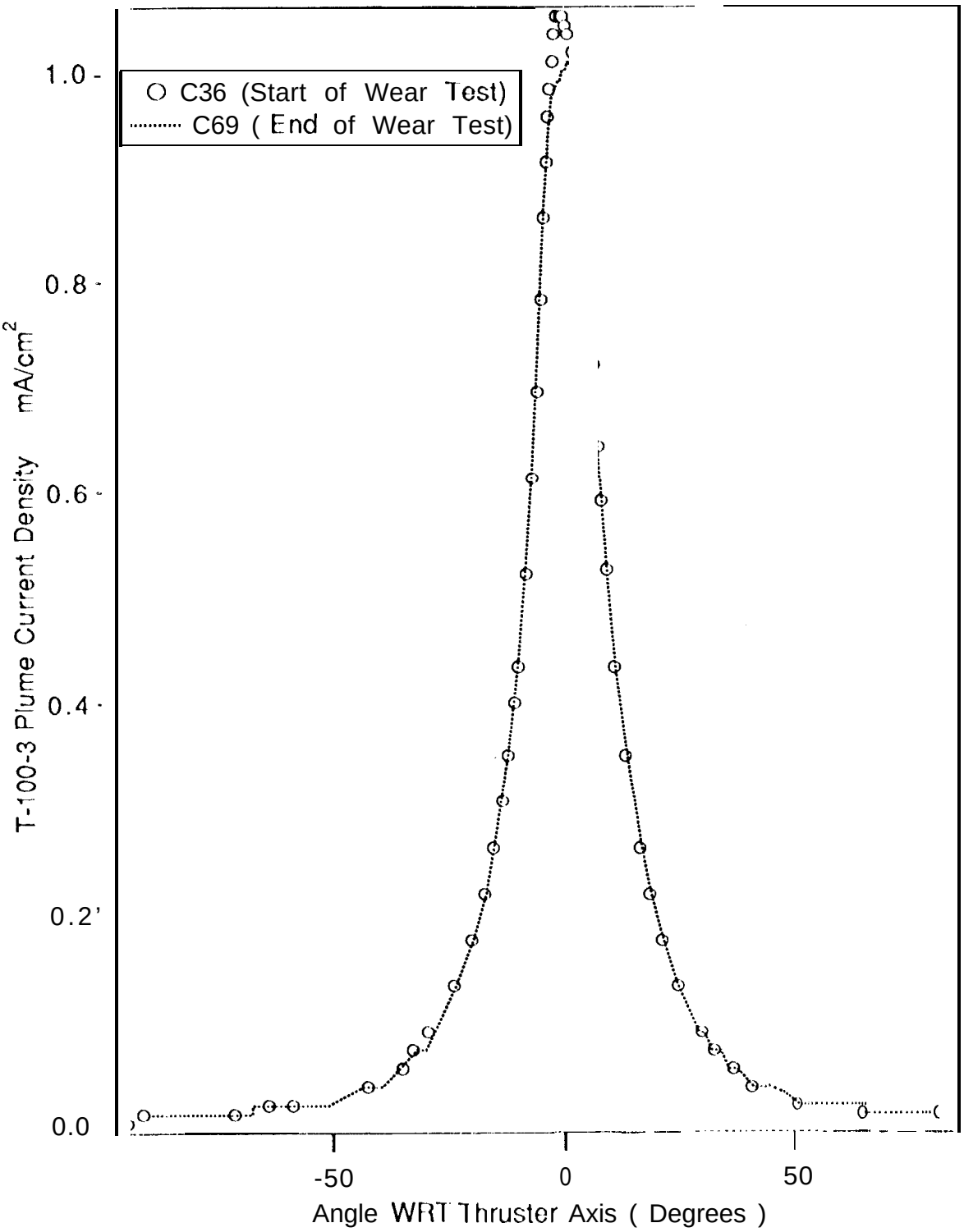


Fig 12

which thruster?


250
200
150
100
50
0
-50
Thruster or Plate Temperature (Degrees C)
T100 Body Temp
Plate Center Temp
Plate Corner Temp
300
250
200
150
100
50
100
200
300
400
500
600
Cumulative Thruster Operating Time (Hrs


C36 (Start of Wear Test)
C69 (End of Wear Test)
T-100-3 Plume Current Density mA/cm2
1.0
0.8
0.6
0.4
0.2
0.0
-50
0
50
Angle WRT Thruster Axis (Degrees)

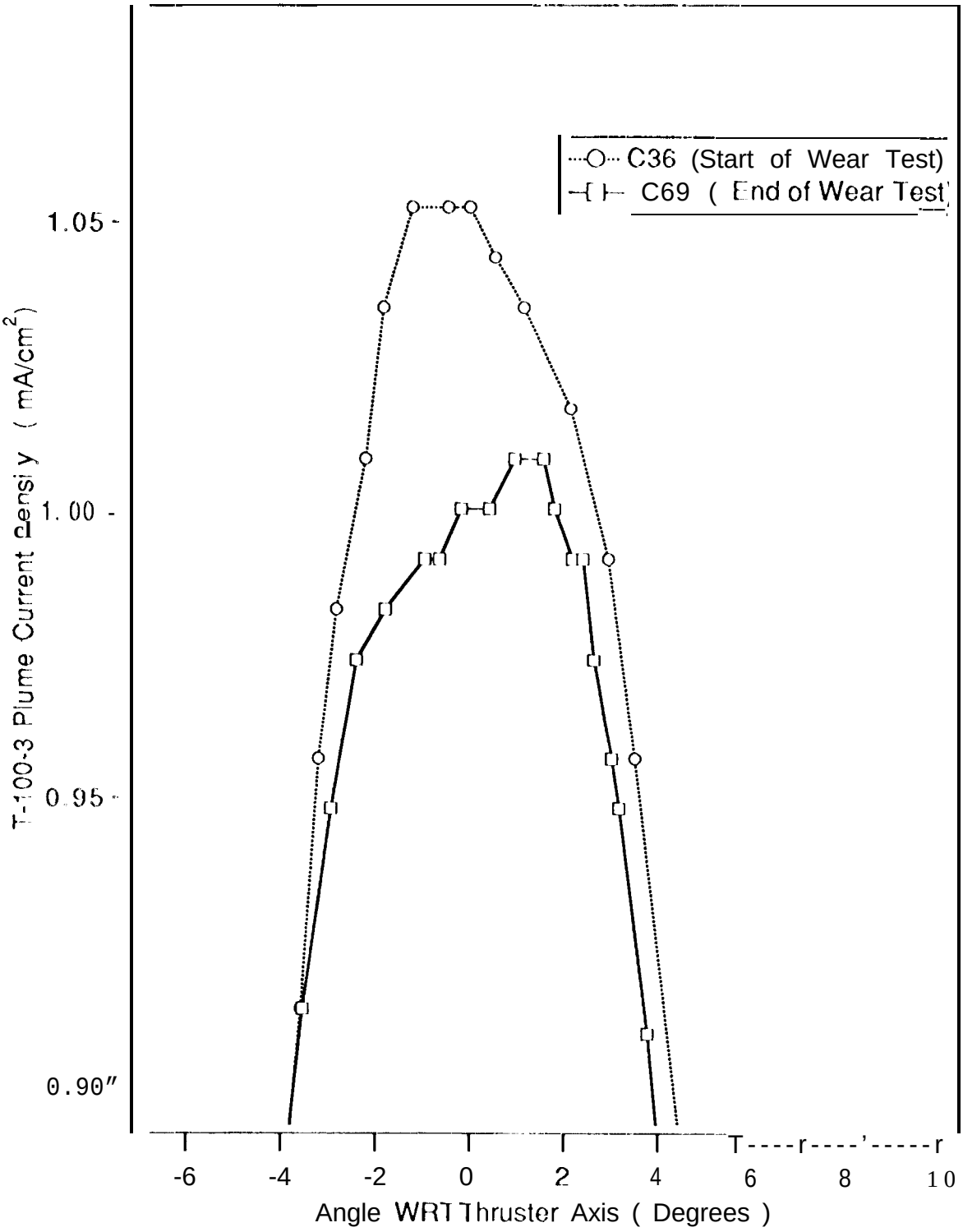

C36 (Start of Wear Test)
C69 (End of Wear Test)
1.05
1.00
0.95
0.90"
T-100-3 Plume Current Density (mA/cm^2)
-6
-4
-2
0
2
4
6
8
10
Angle WRT Thruster Axis (Degrees)

Fig 15

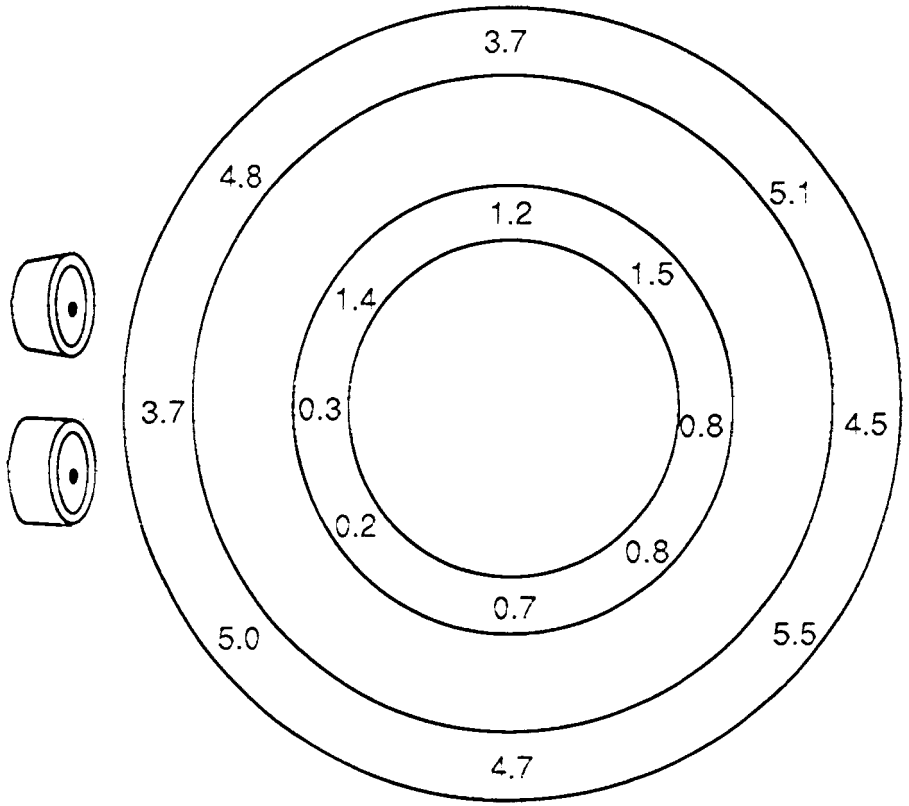


Fig. 16. Insulator erosion in the T-100-3" after completion of the 632-hr wear test. Numbers denote erosion of the insulator in millimeters.

Which Houston?

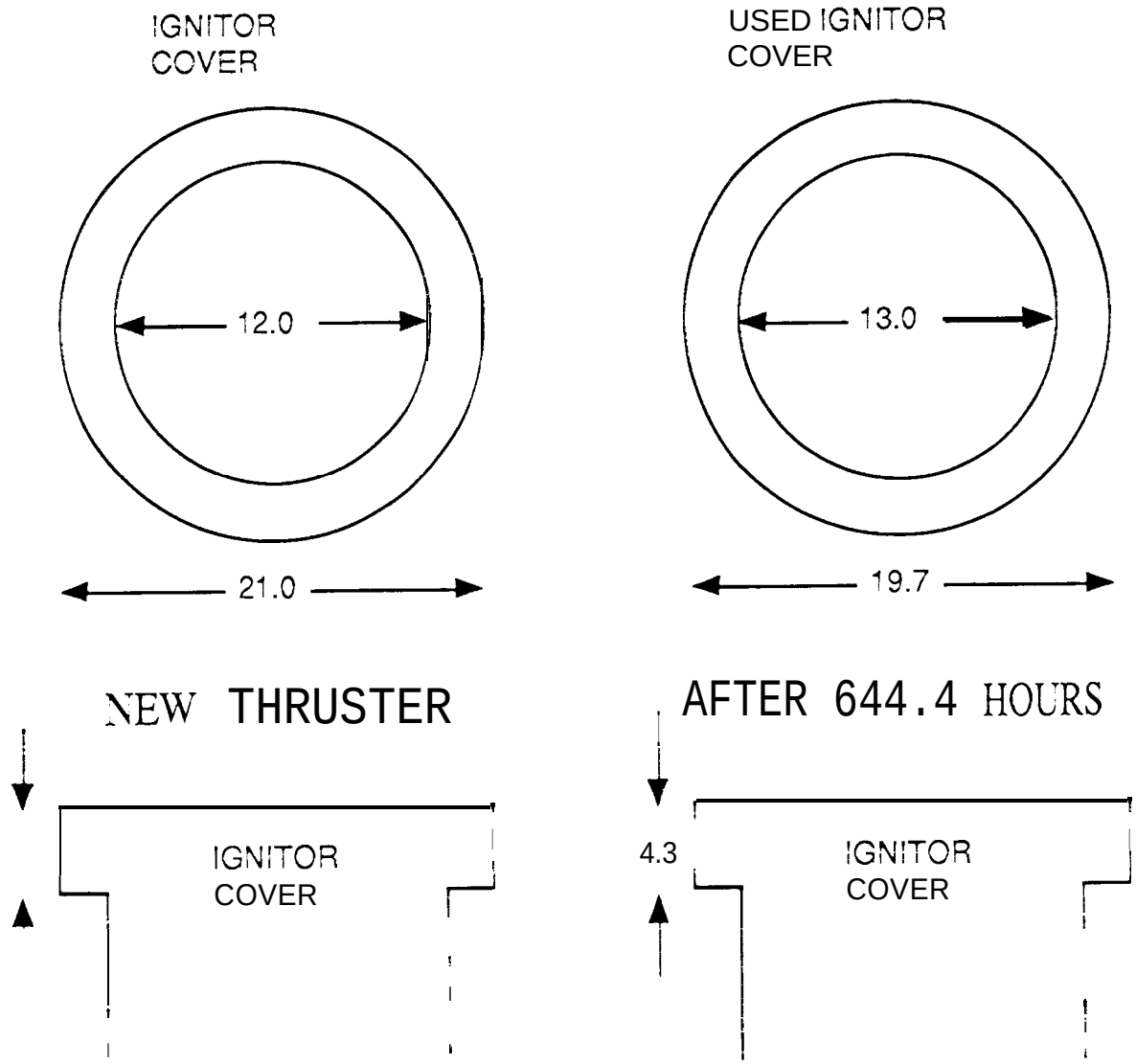


Fig. 17. Ignitor cover wear before and at the completion of the wear test. Numbers denote erosion in mm.

which thruster?

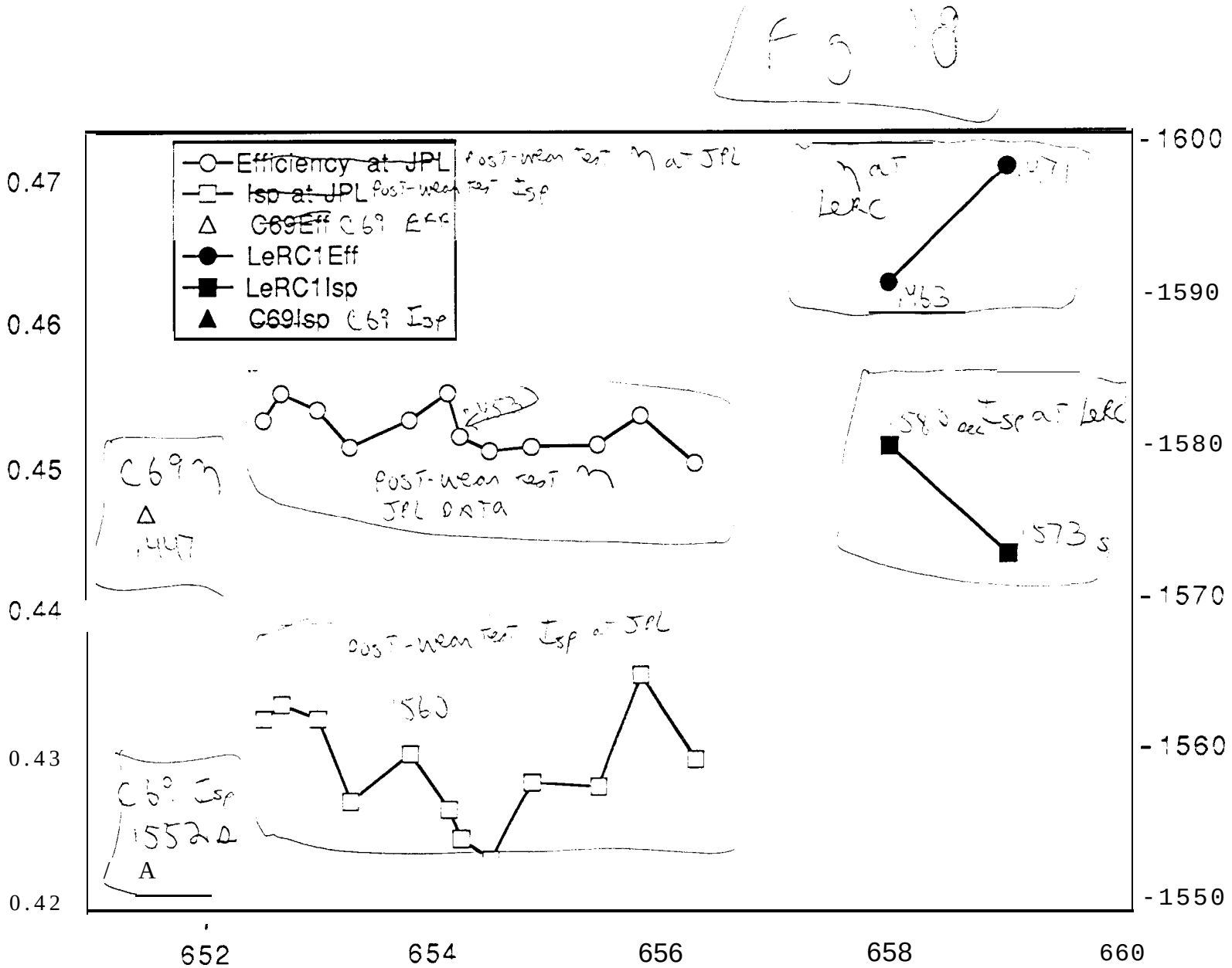
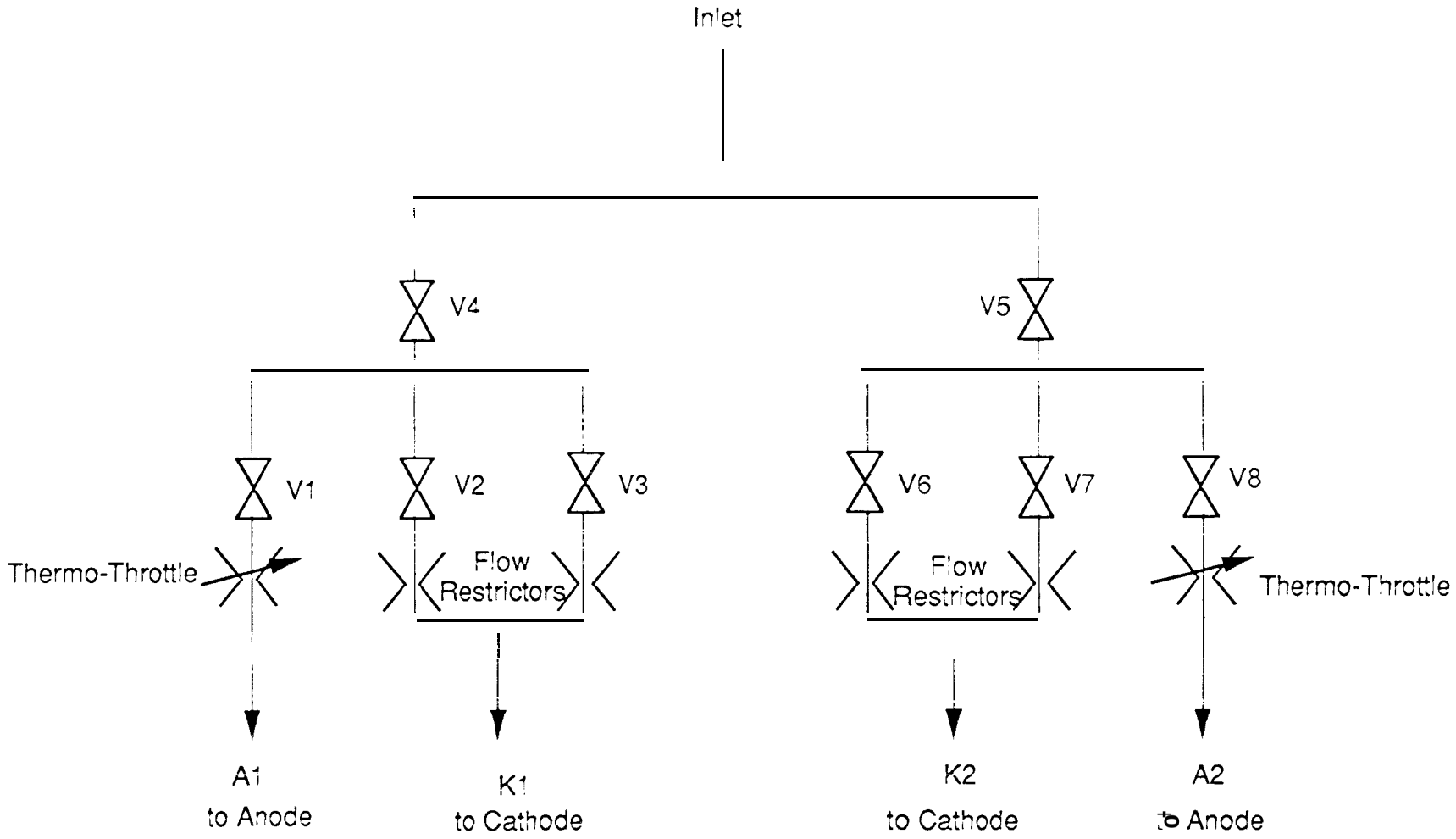


Fig 18
Efficiency at JPL
Isp at JPL
C69Eff
LeRC1Eff
LeRC1Isp
C69Isp
post-wear test η at JPL
post-wear test Isp
η at LeRC
.471
.463
C69 η
Δ
.447
post-wear test η
JPL DATA
1553
580 sec Isp at LeRC
573 s
post-wear test Isp at JPL
560
C69 Isp
1552 Δ
A
0.47
0.46
0.45
0.44
0.43
0.42
1600
1590
1580
1570
1560
1550
652
654
656
658
660
which thruster?


Inlet
V4
V5
V1
V2
V3
V6
V7
V8
Thermo-Throttle
Flow Restrictors
Flow Restrictors
Thermo-Throttle
A1
to Anode
K1
to Cathode
K2
to Cathode
A2
to Anode

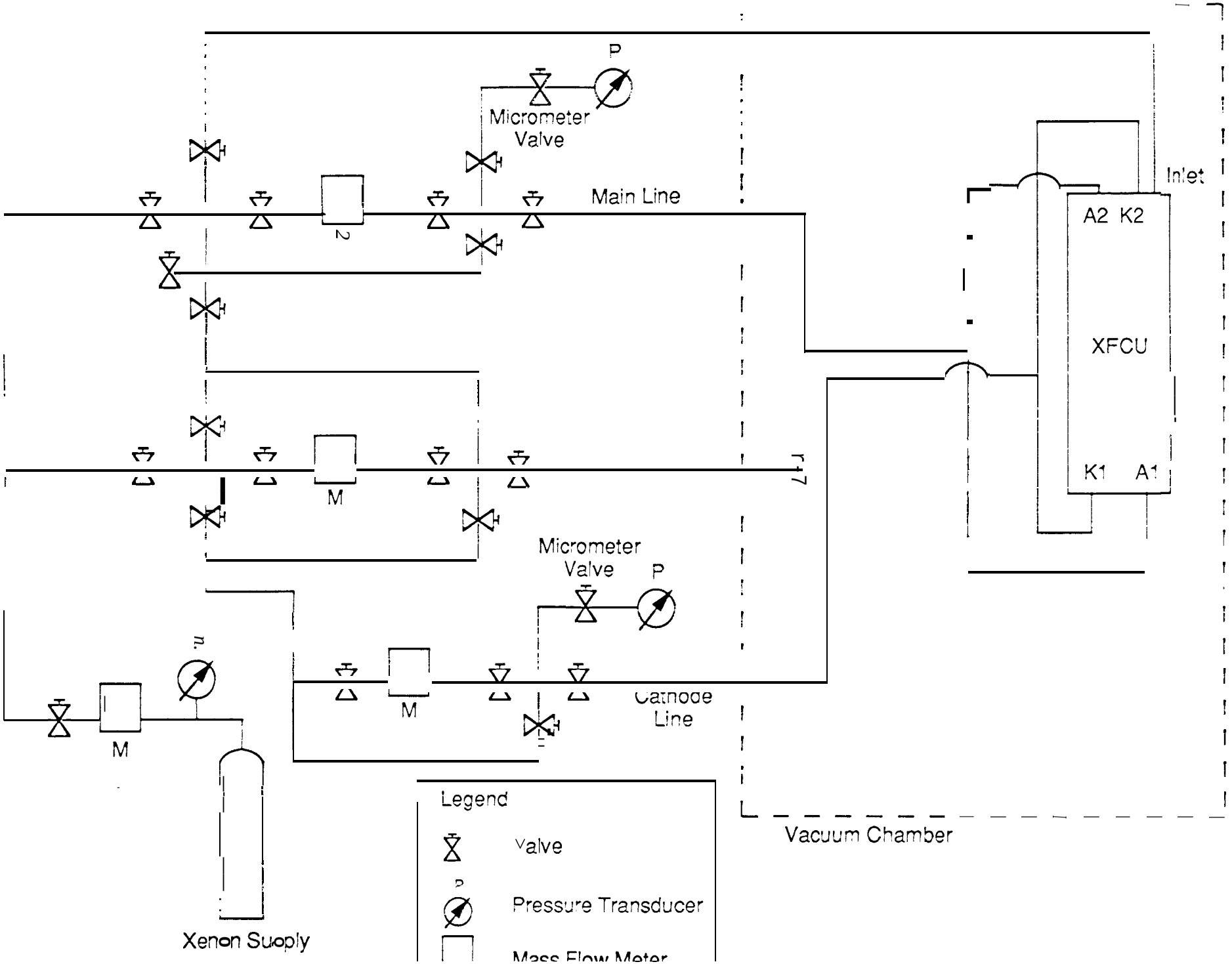

P
Micrometer
Valve
Main Line
Inlet
A2 K2
XFCU
K1 A1
M
Micrometer
Valve
P
M
Cathode
Line
M
Xenon Suoply
Legend
Valve
Pressure Transducer
Mass Flow Meter
Vacuum Chamber

Fig. 21

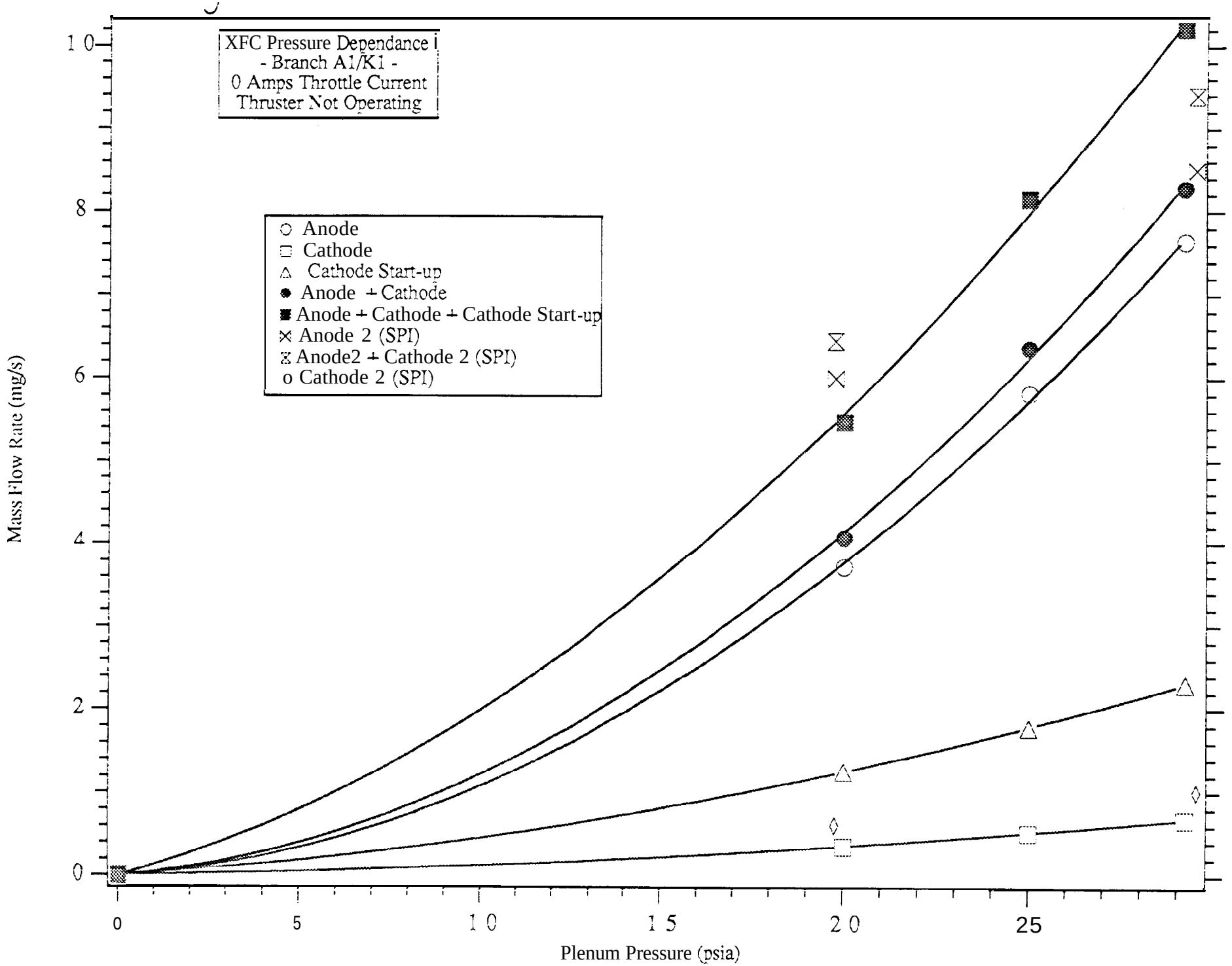

XFC Pressure Dependance
- Branch A1/K1 -
0 Amps Throttle Current
Thruster Not Operating
Anode
Cathode
Cathode Start-up
Anode + Cathode
Anode + Cathode + Cathode Start-up
Anode 2 (SPI)
Anode2 + Cathode 2 (SPI)
Cathode 2 (SPI)
Mass Flow Rate (mg/s)
0
2
4
6
8
10
0
5
10
15
20
25
Plenum Pressure (psia)

Fig 22

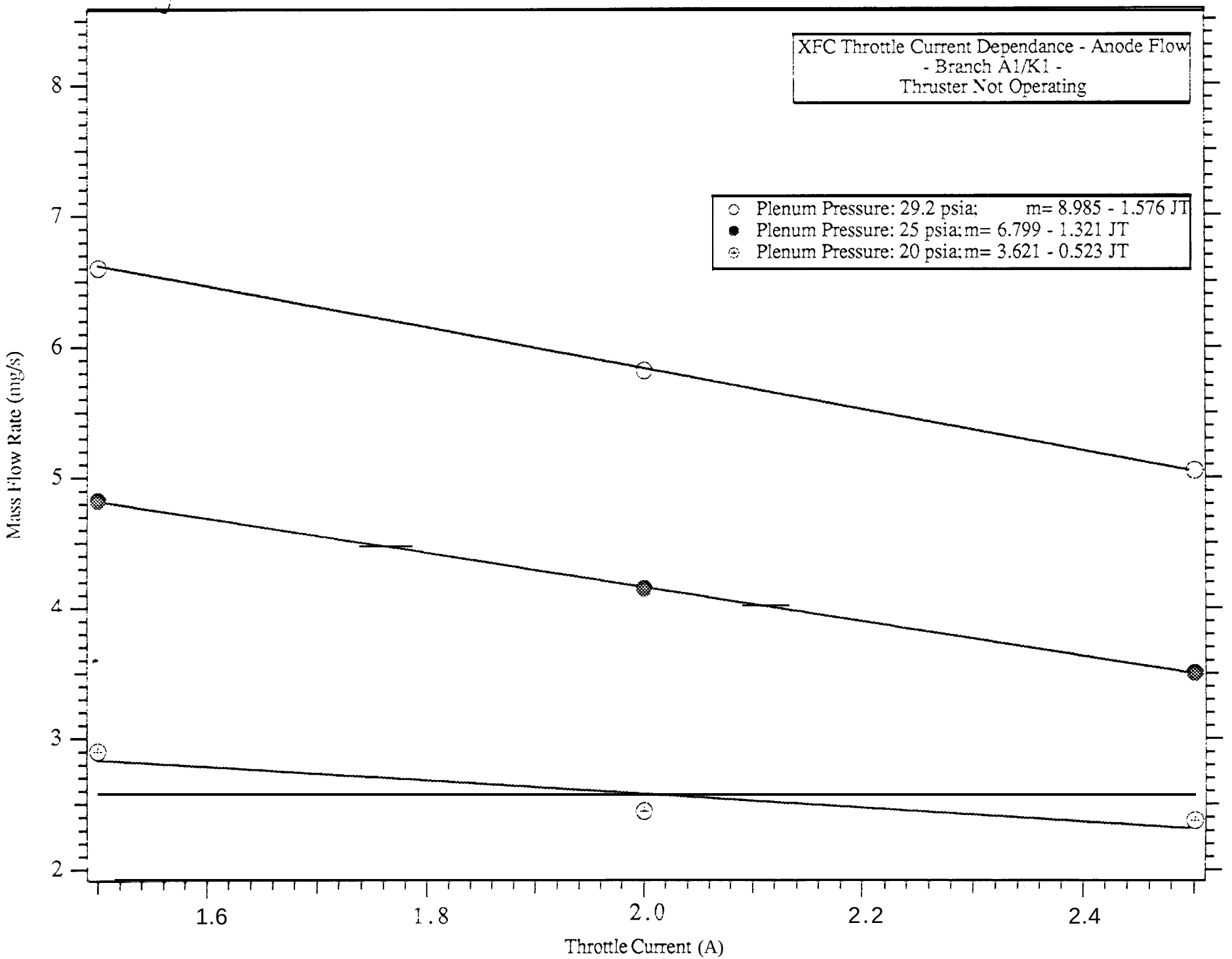
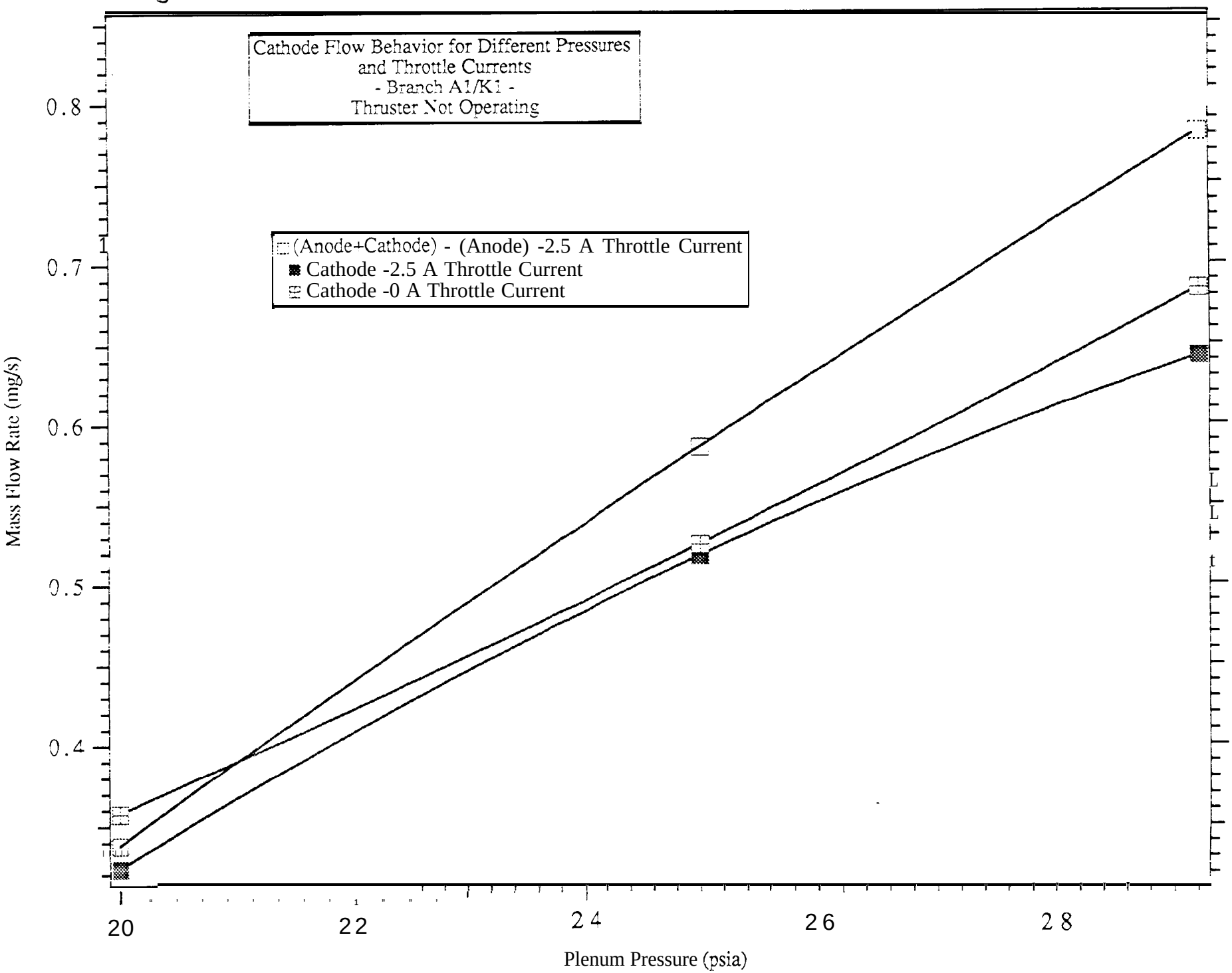

XFC Throttle Current Dependance - Anode Flow
- Branch A1/K1 -
Thruster Not Operating
Plenum Pressure: 29.2 psia; m= 8.985 - 1.576 JT
Plenum Pressure: 25 psia; m= 6.799 - 1.321 JT
Plenum Pressure: 20 psia; m= 3.621 - 0.523 JT
Mass Flow Rate (mg/s)
8
7
6
5
4
3
2
1.6
1.8
2.0
2.2
2.4
Throttle Current (A)

Fig. 23


Cathode Flow Behavior for Different Pressures
and Throttle Currents
- Branch A1/K1 -
Thruster Not Operating
(Anode+Cathode) - (Anode) -2.5 A Throttle Current
Cathode -2.5 A Throttle Current
Cathode -0 A Throttle Current
Mass Flow Rate (mg/s)
0.8
0.7
0.6
0.5
0.4
20
22
24
26
28
Plenum Pressure (psia)

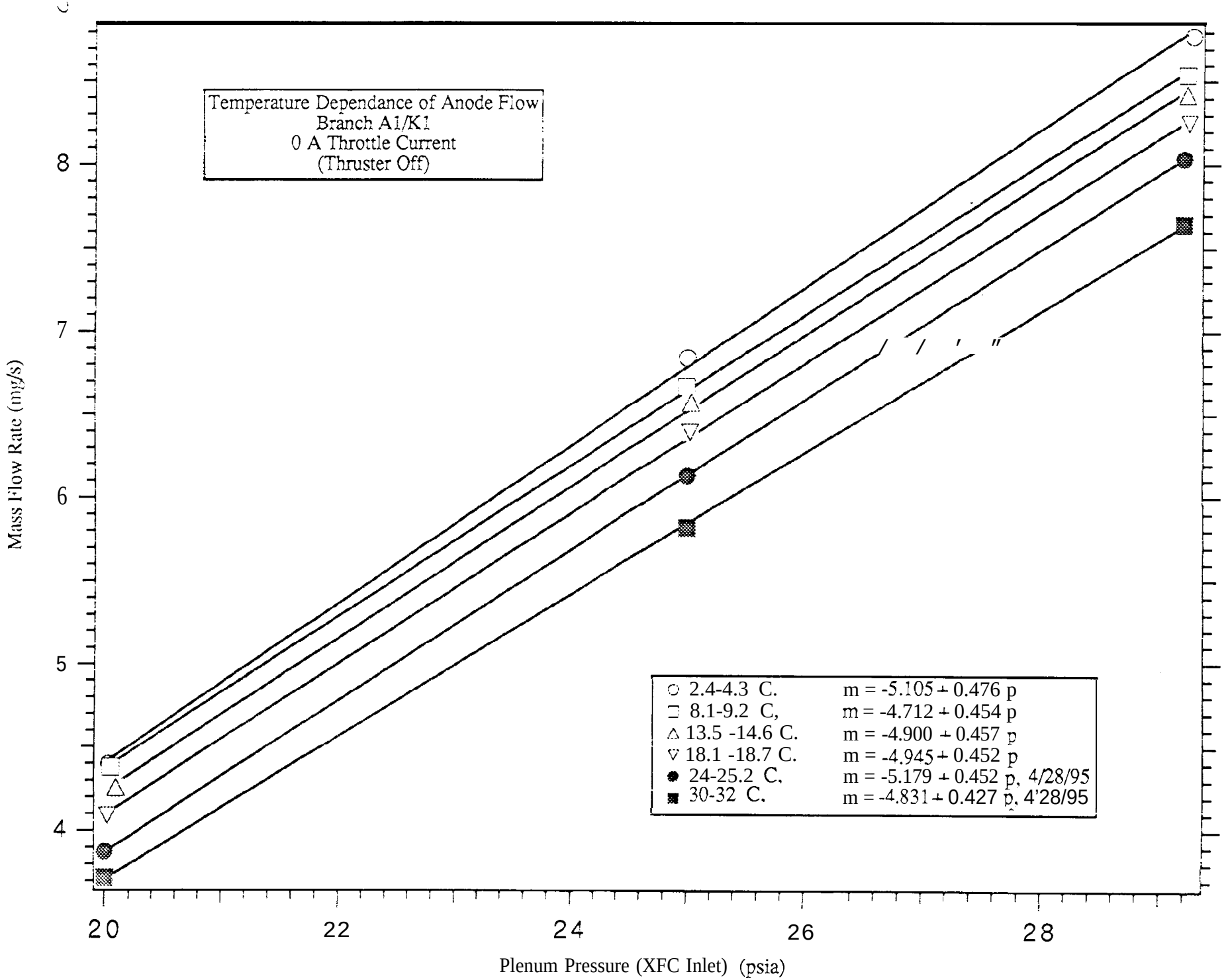

Temperature Dependance of Anode Flow
Branch A1/K1
0 A Throttle Current
(Thruster Off)
Mass Flow Rate (mg/s)
Plenum Pressure (XFC Inlet) (psia)
4
5
6
7
8
20
22
24
26
28
2.4-4.3 C. m = -5.105 + 0.476 p
8.1-9.2 C, m = -4.712 + 0.454 p
13.5 -14.6 C. m = -4.900 + 0.457 p
18.1 -18.7 C. m = -4.945 + 0.452 p
24-25.2 C. m = -5.179 + 0.452 p, 4/28/95
30-32 C. m = -4.831 + 0.427 p, 4'28/95

Fig 25

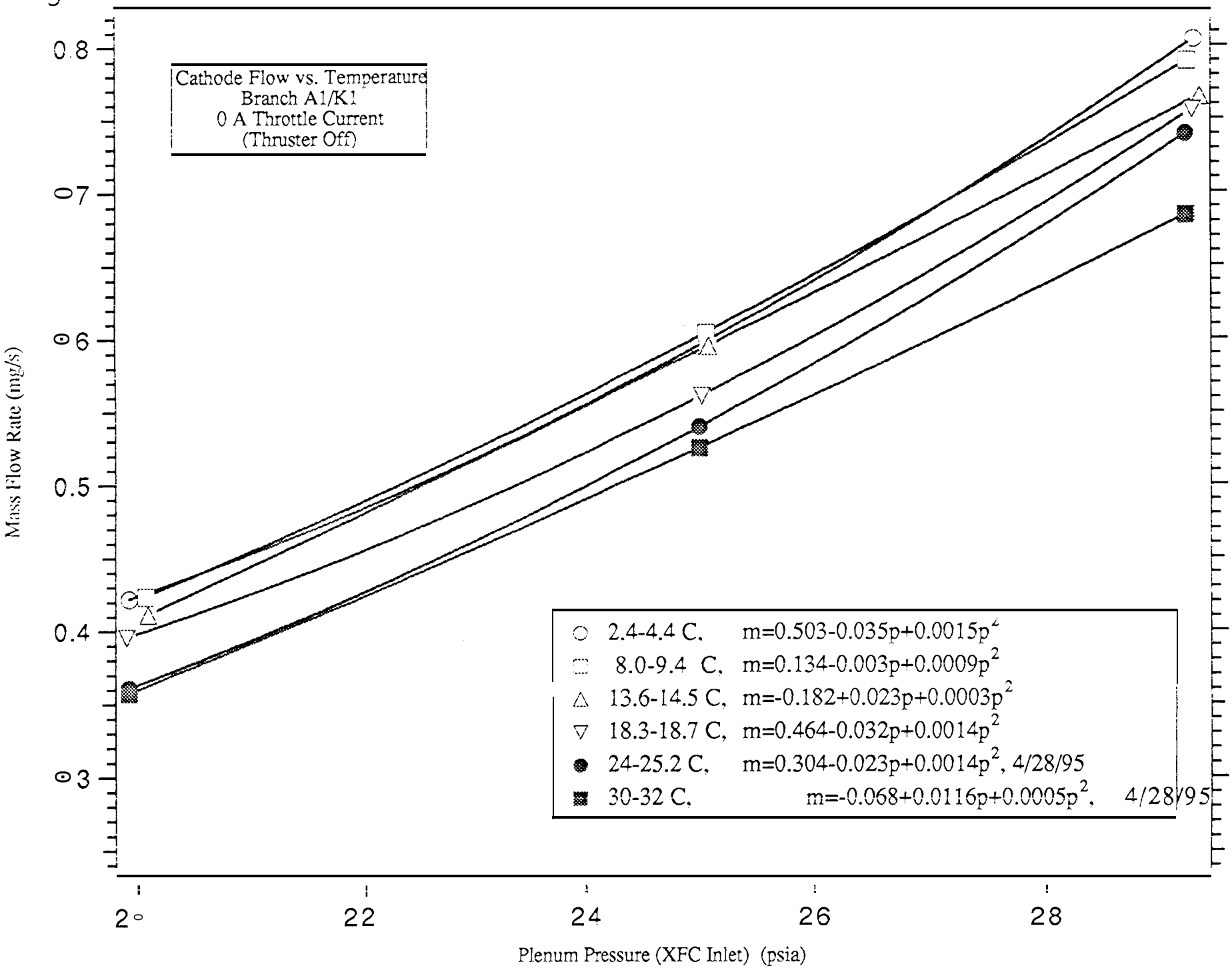

Cathode Flow vs. Temperature
Branch A1/K1
0 A Throttle Current
(Thruster Off)
Mass Flow Rate (mg/s)
0.8
0.7
0.6
0.5
0.4
0.3
20
22
24
26
28
Plenum Pressure (XFC Inlet) (psia)
2.4-4.4 C, m=0.503-0.035p+0.0015p²
8.0-9.4 C, m=0.134-0.003p+0.0009p²
13.6-14.5 C, m=-0.182+0.023p+0.0003p²
18.3-18.7 C, m=0.464-0.032p+0.0014p²
24-25.2 C, m=0.304-0.023p+0.0014p², 4/28/95
30-32 C, m=-0.068+0.0116p+0.0005p², 4/28/95

Fig 26

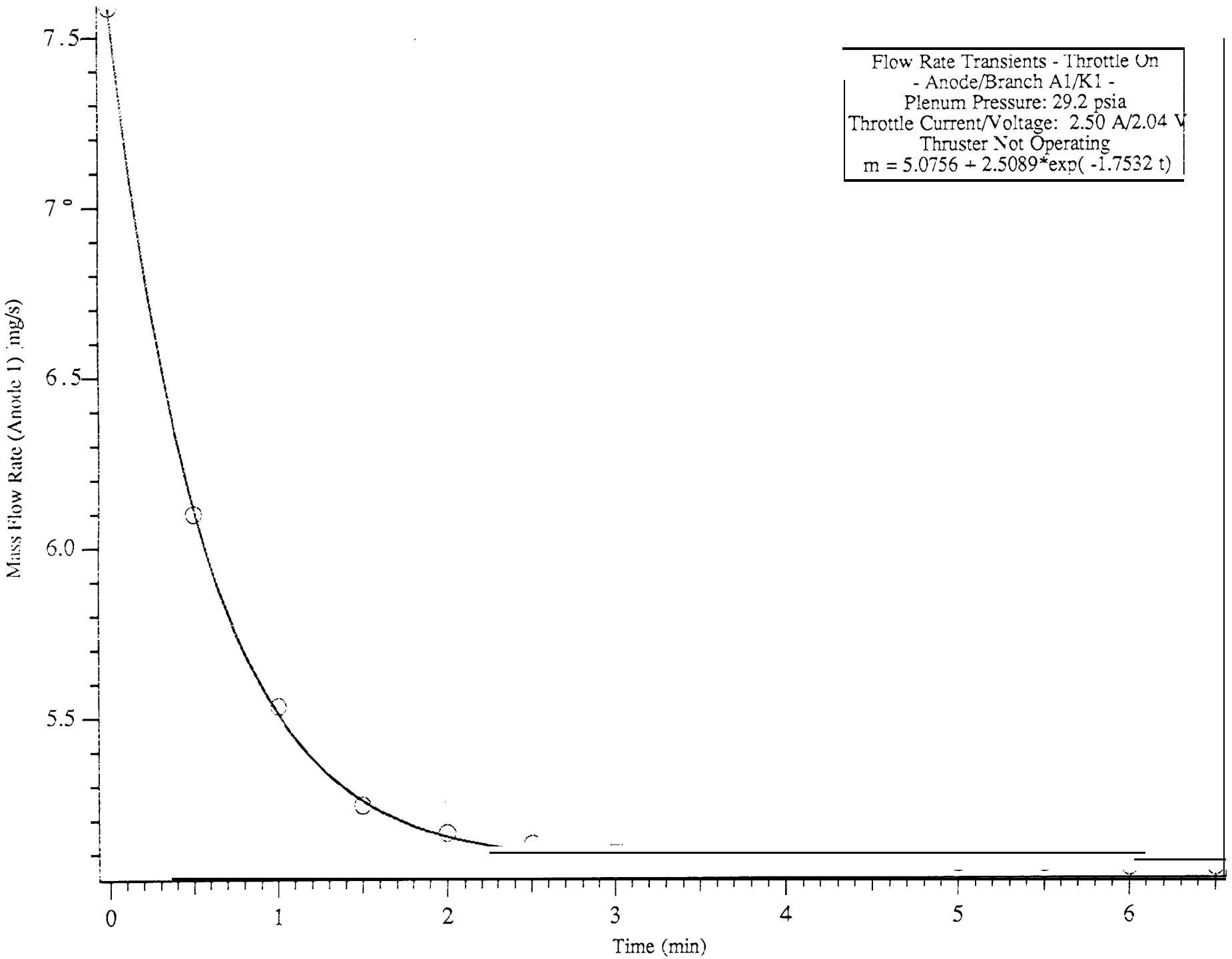
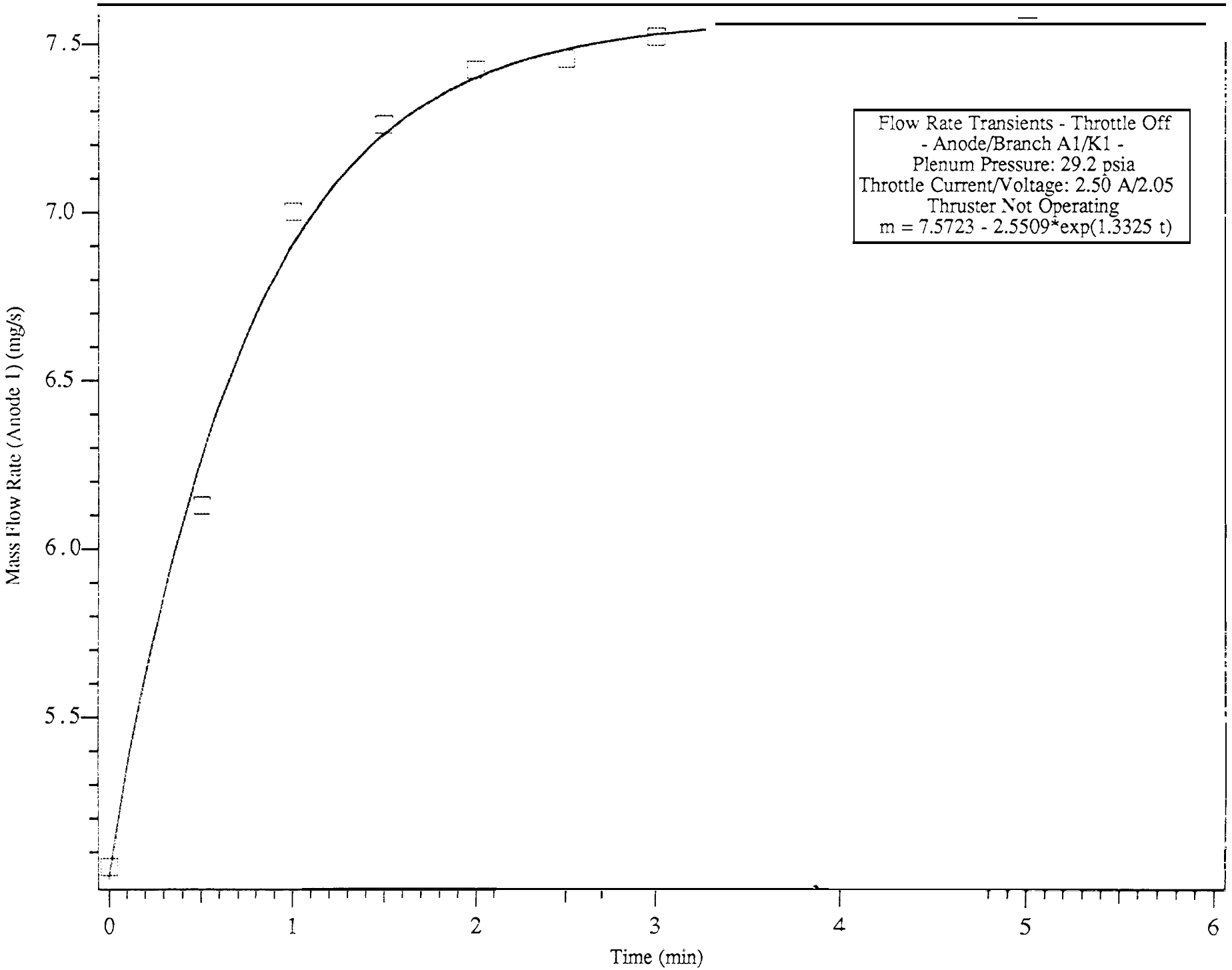
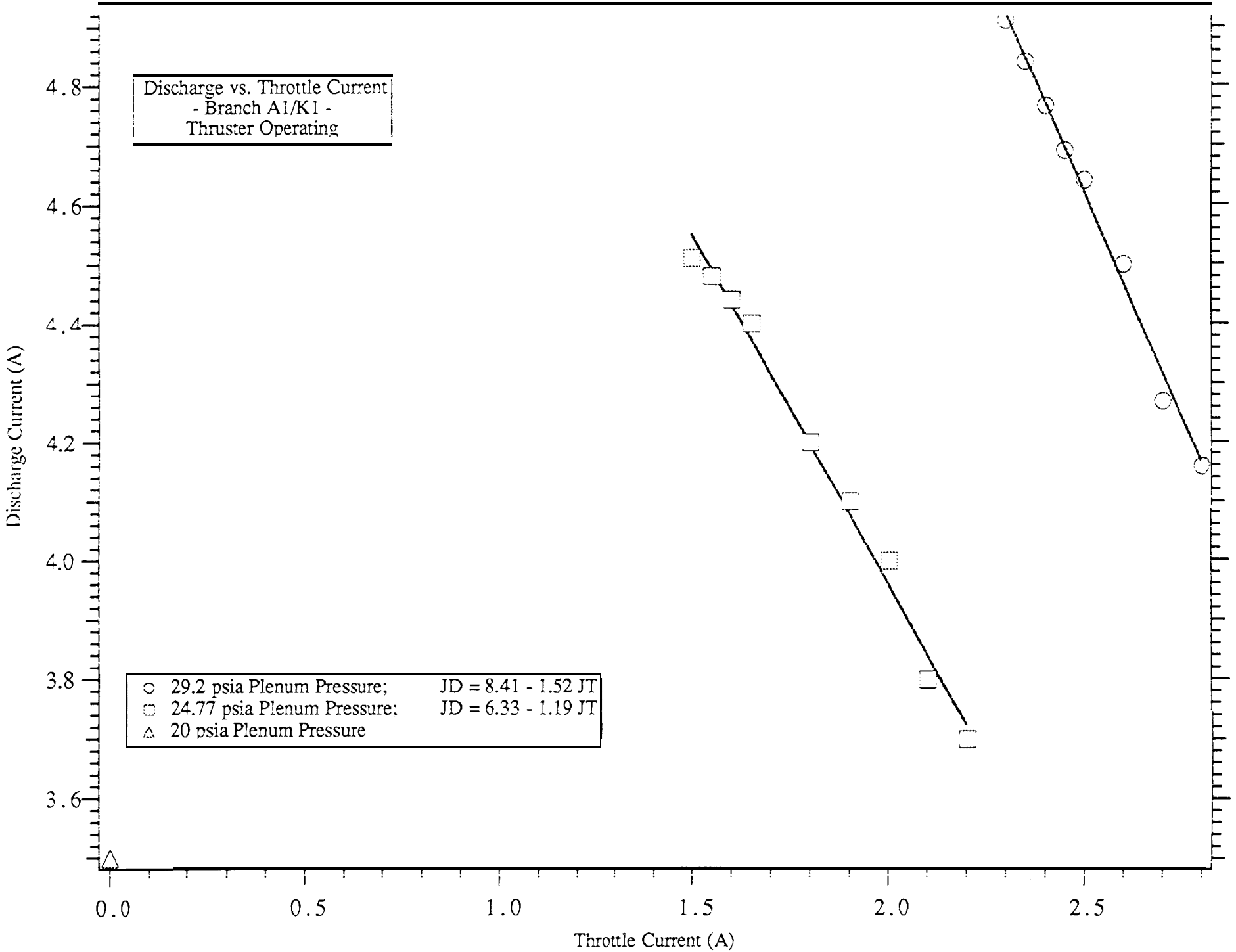

Flow Rate Transients - Throttle On
- Anode/Branch A1/K1 -
Plenum Pressure: 29.2 psia
Throttle Current/Voltage: 2.50 A/2.04 V
Thruster Not Operating
m = 5.0756 + 2.5089*exp(-1.7532 t)
Mass Flow Rate (Anode 1) (mg/s)
7.5
7 °
6.5
6.0
5.5
0
1
2
3
4
5
6
Time (min)

Fig 27


Flow Rate Transients - Throttle Off
- Anode/Branch A1/K1 -
Plenum Pressure: 29.2 psia
Throttle Current/Voltage: 2.50 A/2.05
Thruster Not Operating
m = 7.5723 - 2.5509*exp(1.3325 t)
Mass Flow Rate (Anode 1) (mg/s)
7.5
7.0
6.5
6.0
5.5
0
1
2
3
4
5
6
Time (min)


Discharge vs. Throttle Current
- Branch A1/K1 -
Thruster Operating
4.8
4.6
4.4
4.2
4.0
3.8
3.6
Discharge Current (A)
0.0
0.5
1.0
1.5
2.0
2.5
Throttle Current (A)
29.2 psia Plenum Pressure; JD = 8.41 - 1.52 JT
24.77 psia Plenum Pressure; JD = 6.33 - 1.19 JT
20 psia Plenum Pressure

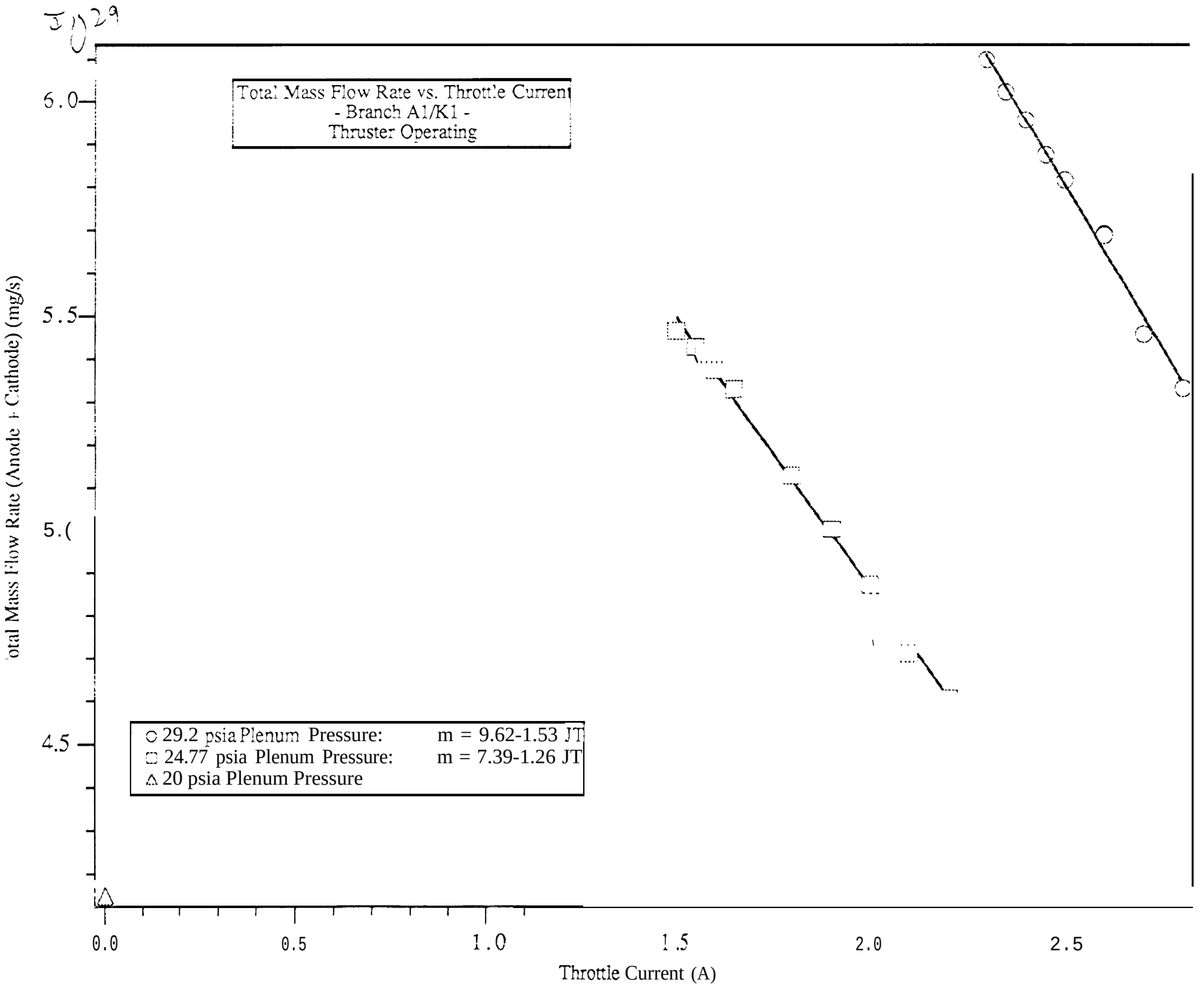

Total Mass Flow Rate vs. Throttle Current
- Branch A1/K1 -
Thruster Operating
6.0
5.5
5.(
4.5
Total Mass Flow Rate (Anode + Cathode) (mg/s)
○ 29.2 psia Plenum Pressure: m = 9.62-1.53 JT
□ 24.77 psia Plenum Pressure: m = 7.39-1.26 JT
△ 20 psia Plenum Pressure
0.0
0.5
1.0
1.5
2.0
2.5
Throttle Current (A)

Fig 30.

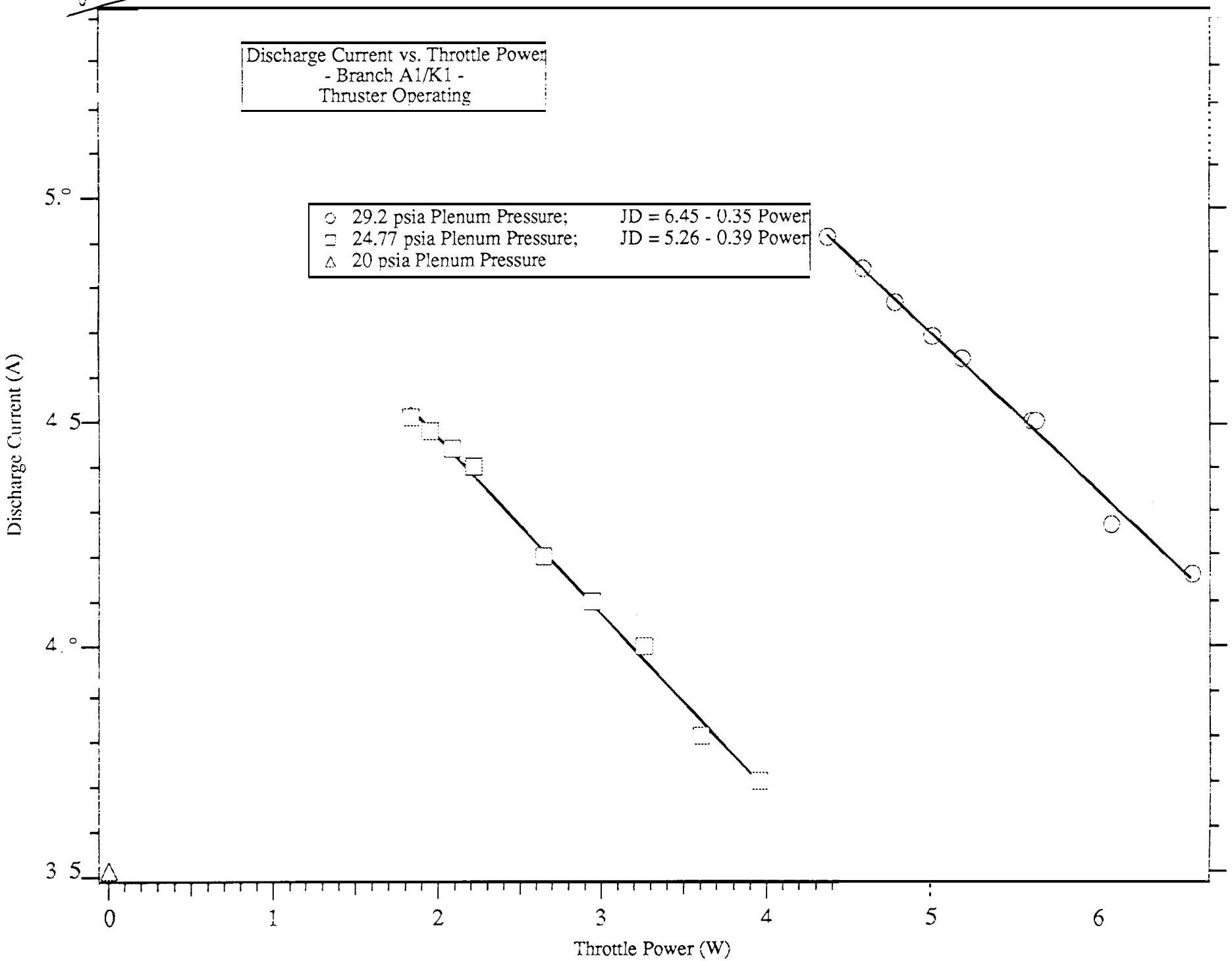

Discharge Current vs. Throttle Power
- Branch A1/K1 -
Thruster Operating
29.2 psia Plenum Pressure; JD = 6.45 - 0.35 Power
24.77 psia Plenum Pressure; JD = 5.26 - 0.39 Power
20 psia Plenum Pressure
Discharge Current (A)
5.°
4 5
4 .°
3 5
0
1
2
3
4
5
6
Throttle Power (W)

Fig. 31

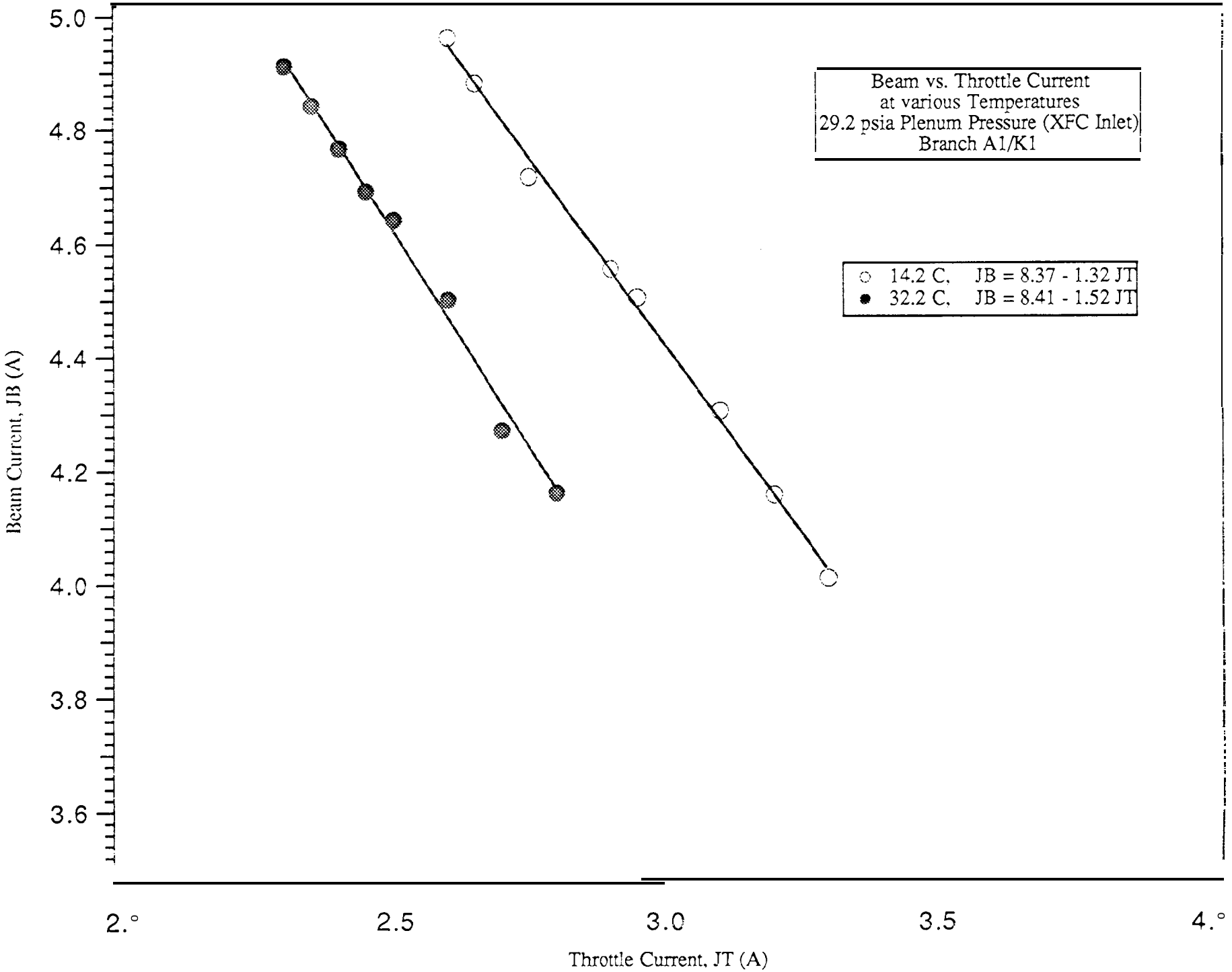
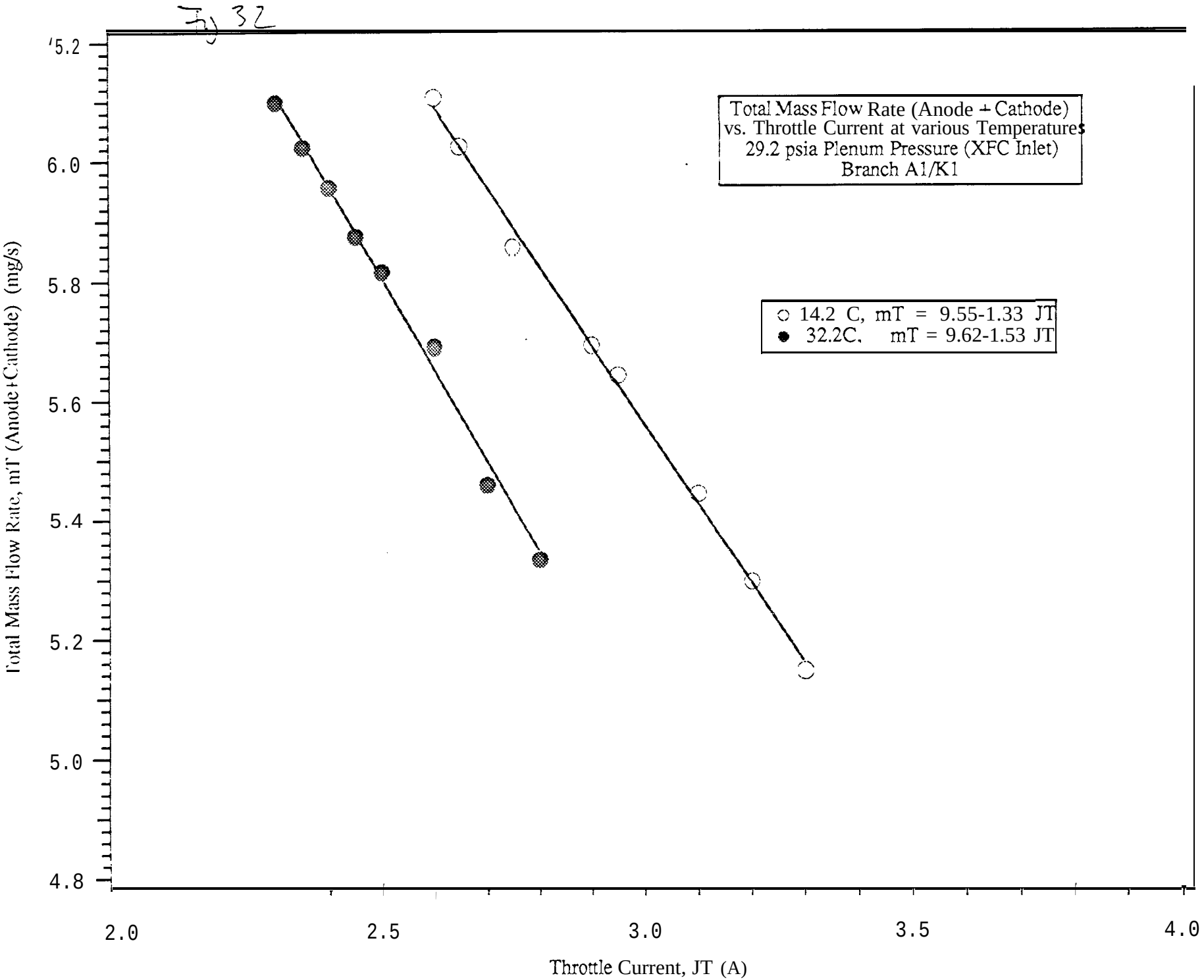
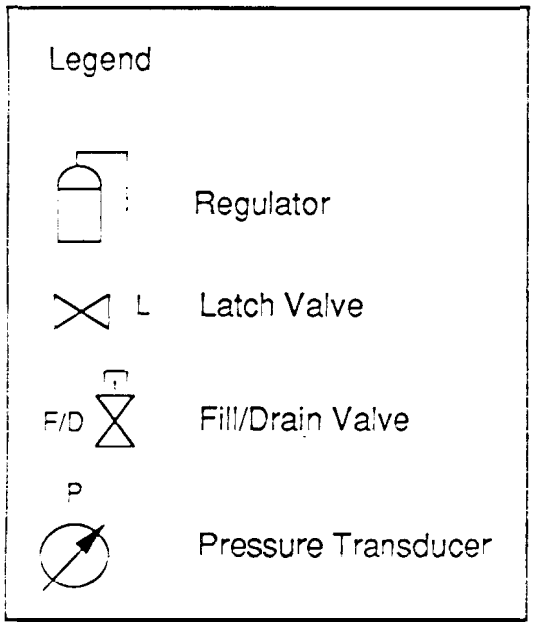
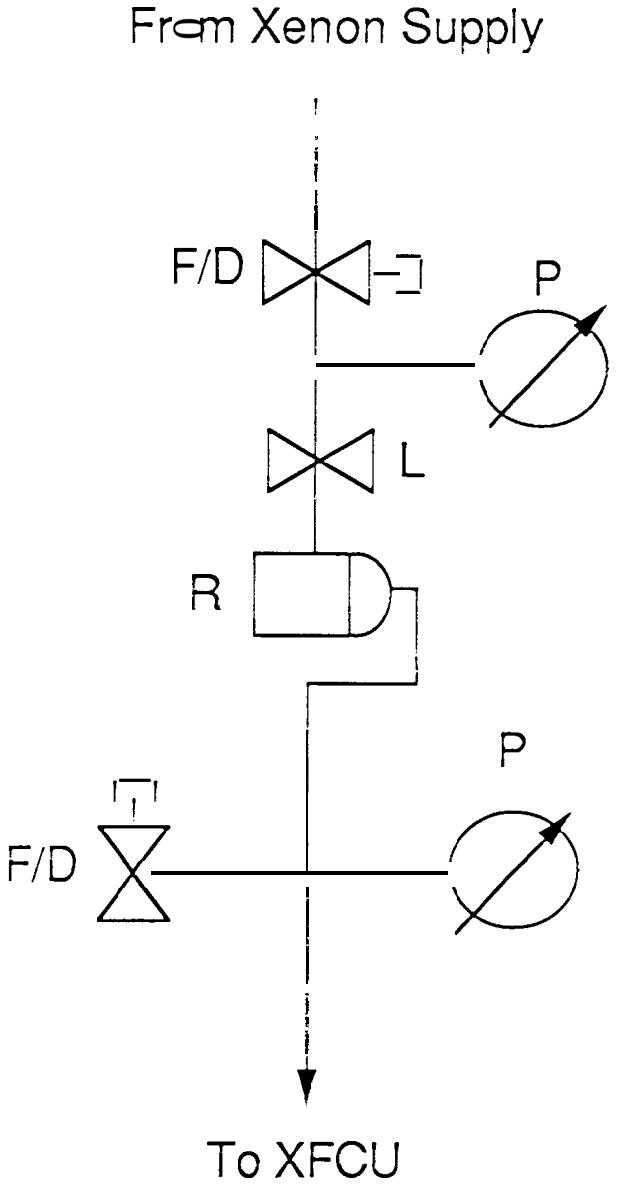
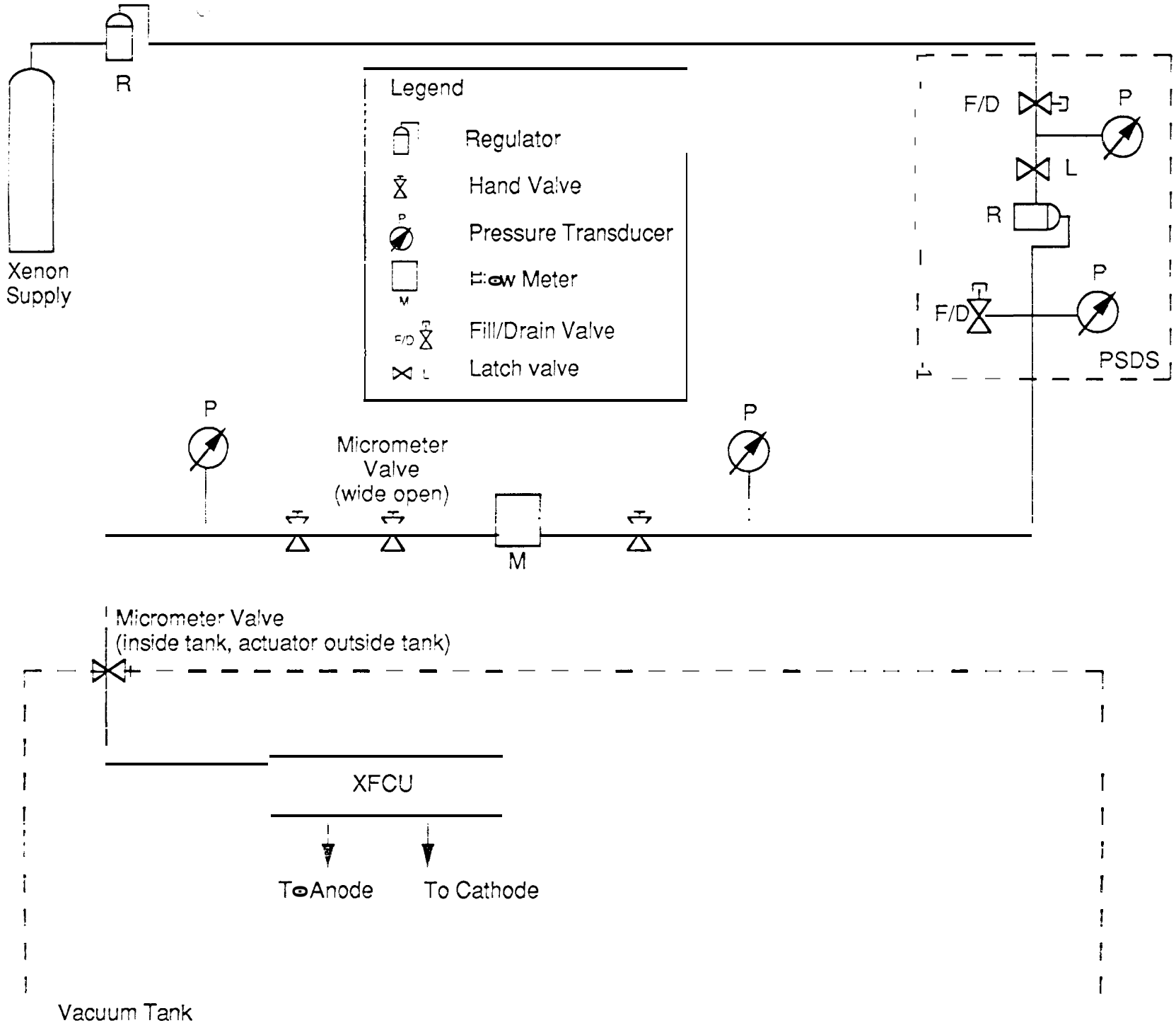

Beam vs. Throttle Current
at various Temperatures
29.2 psia Plenum Pressure (XFC Inlet)
Branch A1/K1
14.2 C. JB = 8.37 - 1.32 JT
32.2 C. JB = 8.41 - 1.52 JT
Beam Current, JB (A)
5.0
4.8
4.6
4.4
4.2
4.0
3.8
3.6
2.°
2.5
3.0
3.5
4.°
Throttle Current, JT (A)

Fig 32


Total Mass Flow Rate (Anode + Cathode)
vs. Throttle Current at various Temperatures
29.2 psia Plenum Pressure (XFC Inlet)
Branch A1/K1
14.2 C, mT = 9.55-1.33 JT
32.2C, mT = 9.62-1.53 JT
Total Mass Flow Rate, mT (Anode+Cathode) (mg/s)
5.2
6.0
5.8
5.6
5.4
5.2
5.0
4.8
2.0
2.5
3.0
3.5
4.0
Throttle Current, JT (A)


Legend
Regulator
L
Latch Valve
F/D
Fill/Drain Valve
P
Pressure Transducer


From Xenon Supply
F/D
P
L
R
P
F/D
To XFCU


R
Xenon
Supply
Legend
Regulator
Hand Valve
Pressure Transducer
Flow Meter
Fill/Drain Valve
Latch valve
F/D
P
L
R
P
F/D
PSDS
P
Micrometer
Valve
(wide open)
P
M
Micrometer Valve
(inside tank, actuator outside tank)
XFCU
To Anode
To Cathode
Vacuum Tank

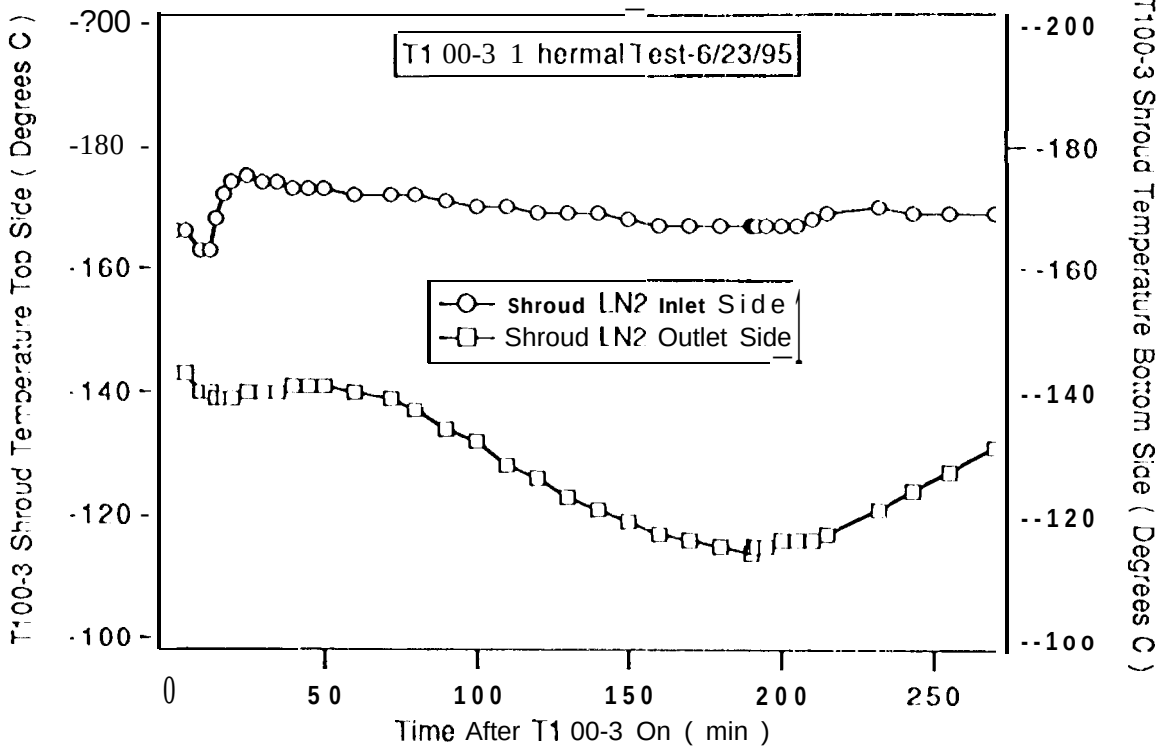
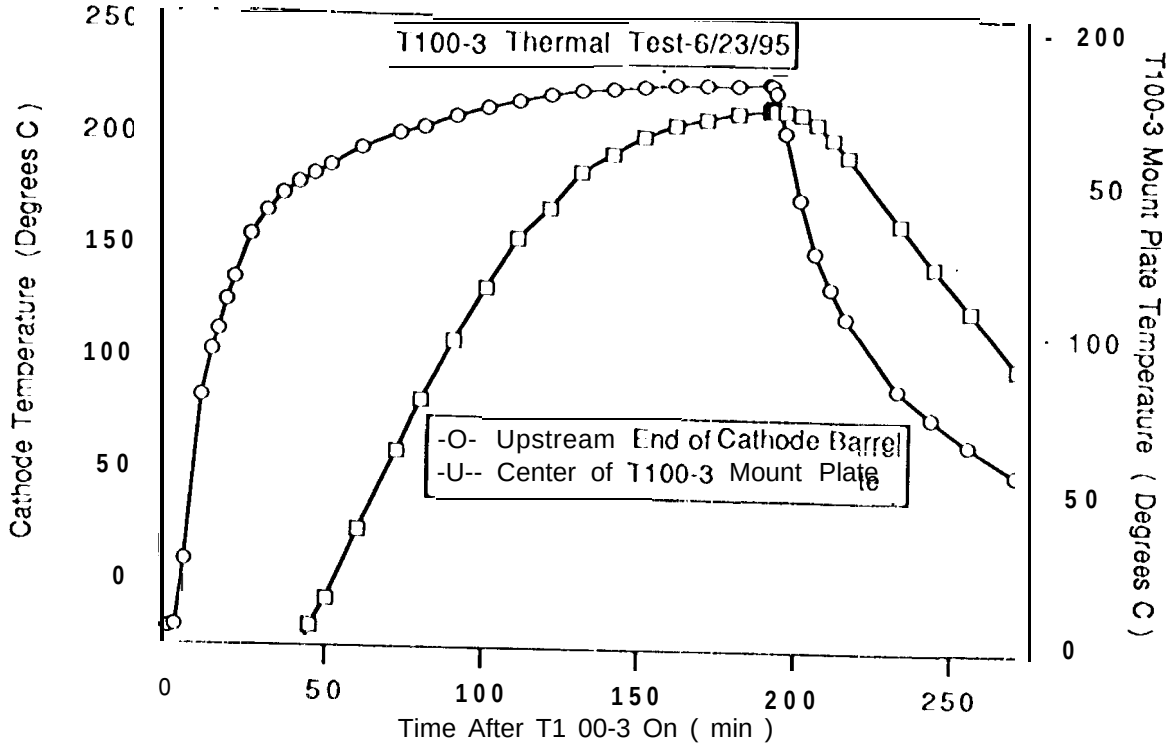
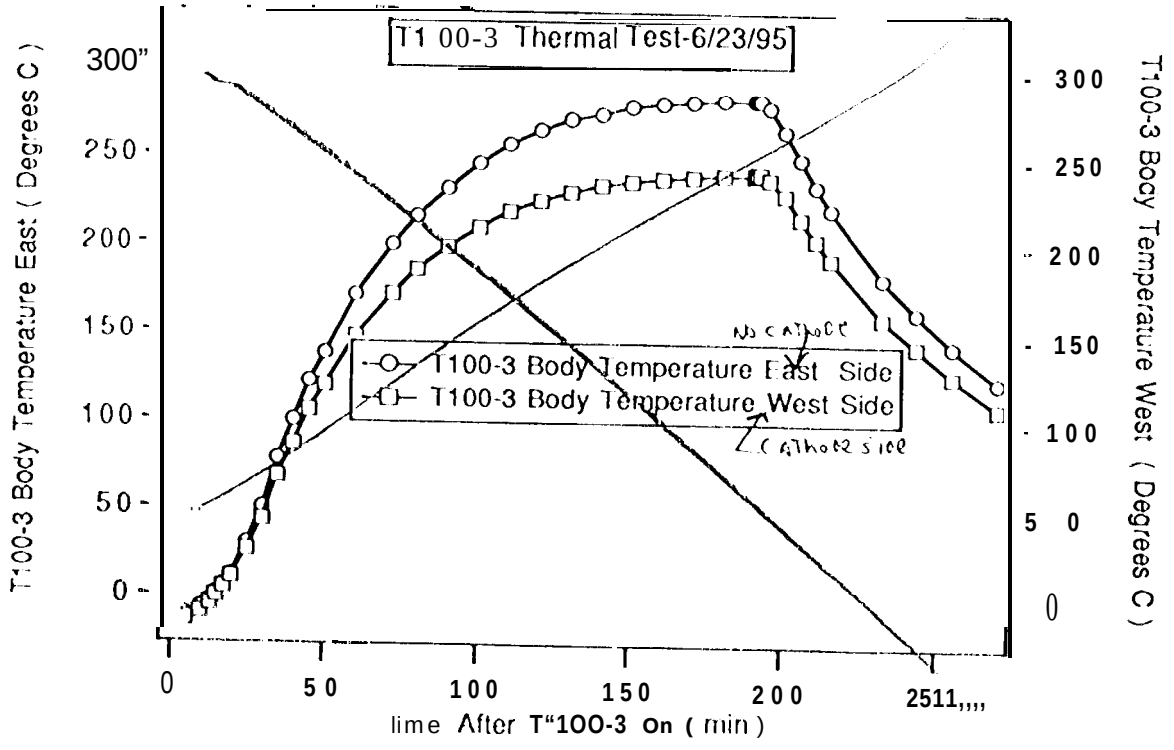

T1 00-3 1 hermal Test-6/23/95
Shroud LN2 Inlet Side
Shroud LN2 Outlet Side
T100-3 Shroud Temperature Top Side (Degrees C)
T100-3 Shroud Temperature Bottom Side (Degrees C)
-?00 -
-180 -
-160 -
-140 -
-120 -
-100 -
--200
--180
--160
--140
--120
--100
0
50
100
150
200
250
Time After T1 00-3 On (min)

Fig 36

Fig 8937


T100-3 Thermal Test-6/23/95
Cathode Temperature (Degrees C)
T100-3 Mount Plate Temperature (Degrees C)
-O- Upstream End of Cathode Barrel
-U-- Center of T100-3 Mount Plate
Time After T1 00-3 On (min)
0
50
100
150
200
250


T1 00-3 Thermal Test-6/23/95
T100-3 Body Temperature East (Degrees C)
T100-3 Boay Temperature West (Degrees C)
T100-3 Body Temperature East Side
T100-3 Body Temperature West Side
lime After T"100-3 On (min)
0
50
100
150
200
250
300

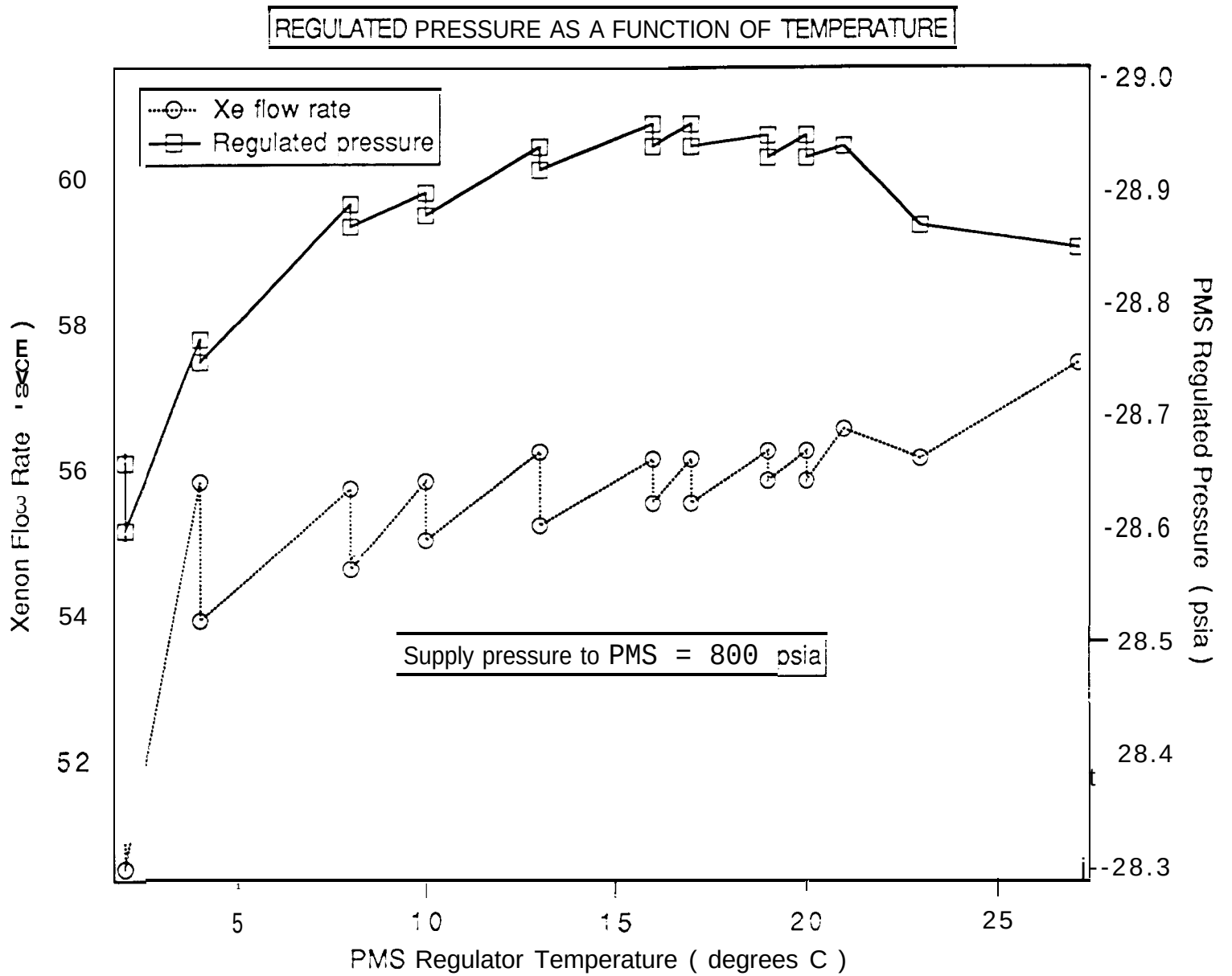

REGULATED PRESSURE AS A FUNCTION OF TEMPERATURE
Xe flow rate
Regulated pressure
Supply pressure to PMS = 800 psia
Xenon Flow Rate (sccm)
PMS Regulated Pressure (psia)
PMS Regulator Temperature (degrees C)
60
58
56
54
52
29.0
28.9
28.8
28.7
28.6
28.5
28.4
28.3
5
10
15
20
25

Fig 38

GIMS TABLE 2

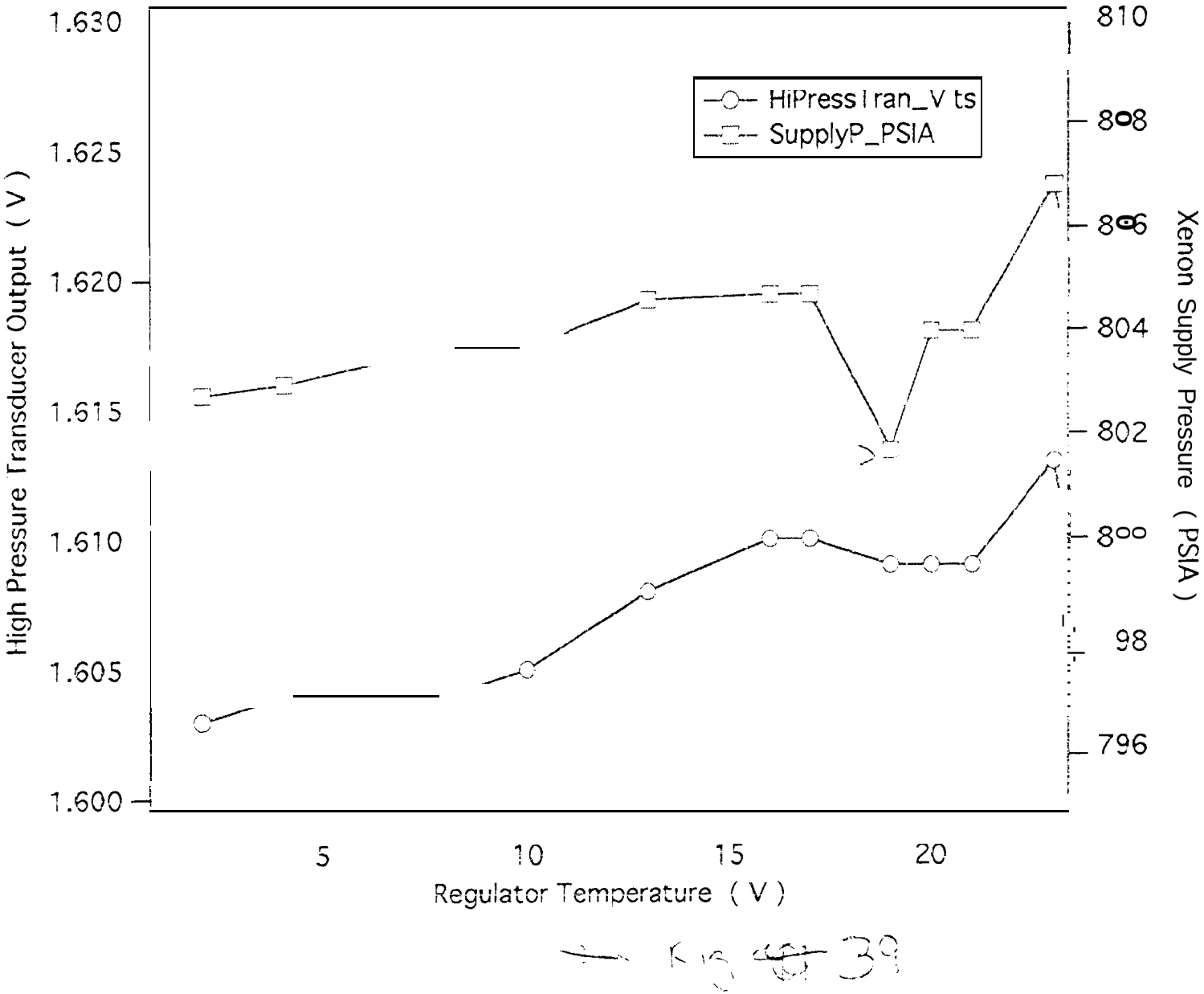


FIG 39